INDEX

ABBREVIATIONS

AAROM	Active Assisted Range of Motion
ALCL	Artificial Lateral Collateral Ligament
AROM	Active Range of Motion
BID	Twice a day
BIS	Bispectral Index
CBC	Complete Blood Count
CCL	Caudal Cruciate Ligament
CrCL	Cranial Cruciate Ligament
COX	Cycloxygenase
CPG	Control Physiotherapy Group
CT	Computer Tomography
DJD	Degenerative Joint Disease
EPG	Early Physiotherapy Group
ESF	External Skeletal Fixation/Fixator
Et	End tidal
FESSA	Fixateur Externe du Service de Santé des Armées
HLESF	Hinged Linear External Skeletal Fixator
ICR	Instant Center of Rotation
IM	Intramuscular
IM-Pin	Intramedullary Pin
LCL	Lateral Collateral Ligament
MCL	Medial Collateral Ligament
MRI	Magnetic Resonance Imaging
PMA	Poly-methyl-acrylate
PO	per os
PROM	Passive Range of Motion
ROM	Range of Motion
SC	Subcutaneous
SID	Once a day
TC	Thigh Circumference
TPLO	Tibial Plateau Levelling Osteotomy
TS	Total Solids
TTh	Thigh Thickness

1 Summary

To evaluate the combination of the FESSA-HLESF/lateral collateral ligament prosthesis in repairing the stifle joint and to study the effect of early physical therapy, eight feral pigeons were divided in two groups. One started physical therapy one day post surgery, and the controls after the HLESF removal (3rd postoperative week). Healing was monitored with clinical, radiographic, pathologic and histologic criteria for six weeks. The combined technique stabilized the joint successfully, and clinically all birds used their limbs normally. Range of motion (ROM) was reduced in all birds (5^{o} in flexion, 40^{o} in extension). No significant difference was detected between the groups in ROM, thigh thickness and circumference or muscle/joint histology. Regressive lameness and pododermatitis (grade I) affected all birds. Fibrosis of the operated joint capsule, reduced synovial fluid and excessive callus were also detected (75% of cases). Muscle histology indicated atrophy of the operated limb (mean fiber Ø 49 µm). Joint histology revealed inaccurate reposition and osteophytes in 62.5%. Remodelling of subchondral and trabecular bone was unremarkable (<5 new osteoid areas/ bone). Common structural abnormalities, associated with remobilization, were the presence of pannus/surface irregularities (25%) and radial clefts (12.5%). In conclusion, the clinical interpretation of a stabilized joint should be made with caution, as intraarticular structures are highly impacted during remobilization.

2 Introduction

Luxations are one of the orthopedic conditions frequently presented to the avian practioner. These may be primary or secondary to fractures. Despite the fact that no concrete prevalence study has yet been submitted, it is generally accepted that differences in luxation type and location can be found according to the lifestyle of the avian patient, influencing also the decision-making on the management, the treatment method selection, and the prognosis. Wing and thoracic girdle luxations occur mostly in wild birds, and pelvic, hind limb and skull luxations in captive birds.

It is widely perceived that luxations are lost cases, especially in wild birds and challenging to manage, if not presented early enough. Various methods, ranging from conservative management and cage rest to explicit invasive surgical procedures have been proposed, which are mainly derived from the experiences in fracture management. For example the FESSA external fixator has been recently demonstrated as a successful tool for fracture management in avian patients even in birds below 1 kg body weight (Hatt et al. 2007). The various diameter tubes are strong, leight, allow gradual dynamization and can be combined in a number of ways producing different types of external skeletal fixators. This offers more options in different species and different type of fractures. Physical therapy after orthopedic surgical procedures is regularly applied and considered as the missing link of the patient rehabilitation to include in a balanced therapeutic scheme.

In this study, a new fixation method and the use of early physical therapy were investigated, with the aim to improve the knowledge on femorotibial joint management.

3 Literature Review

3.1 Anatomical description of the avian femorotibial joint

The femorotibial joint is a ***synovial joint***, which is defined as a joint in which the opposing bony surfaces are covered with a layer of *hyaline cartilage or fibrocartilage*, the presence of a *joint cavity* containing *synovial fluid*- lined with *synovial membrane* and reinforced by a fibrous capsule and ligaments- and there is some *degree of free movement* possible (Benjamin 1999). Other synonyms that may be used are: articulatio synovialis, diarthrodial joint, diarthrosis, junctura synovialis, movable joint or perarticulation.

The basic components of a synovial joint are depicted in Figure 1. They can be separated in extra and intra-articular. These will be presented in detail in the following paragraphs. Published data on the embryonic development of the avian femorotibial joint exists from as early as the end of the 19th and start of 20th centuries (see Fig. 2) (Hepburn 1889; Lubosch 1910; Fell 1925; Niven 1933; Fell 1934; Muratori and Franceschini 1945; Martin 1954).

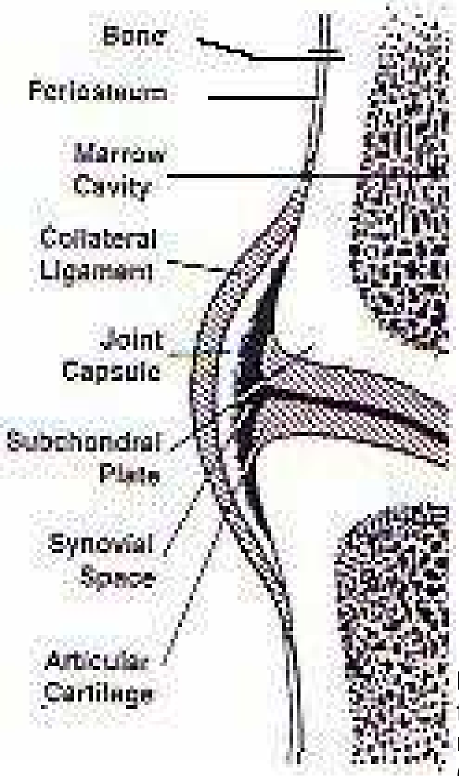


Figure 1: The major components of a movable joint

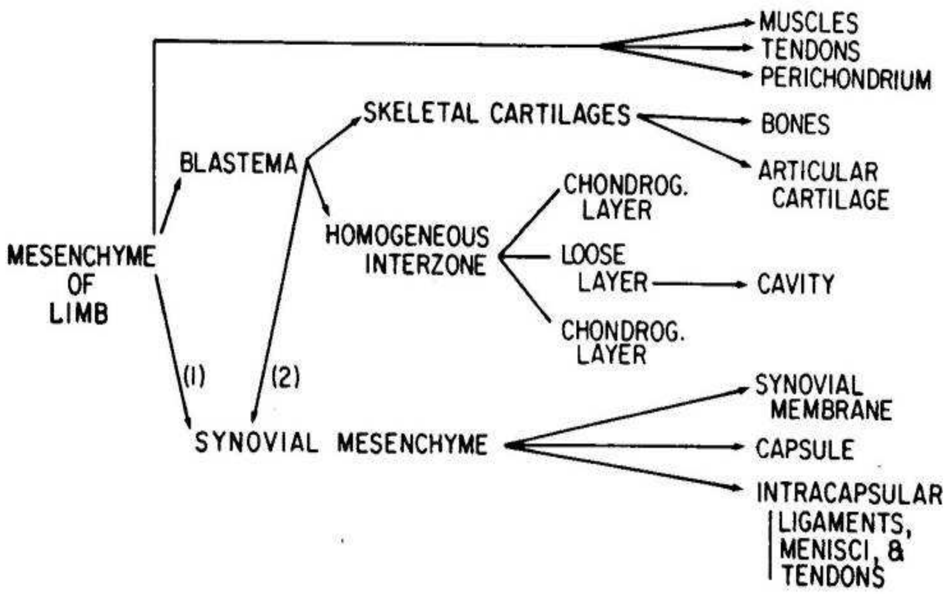
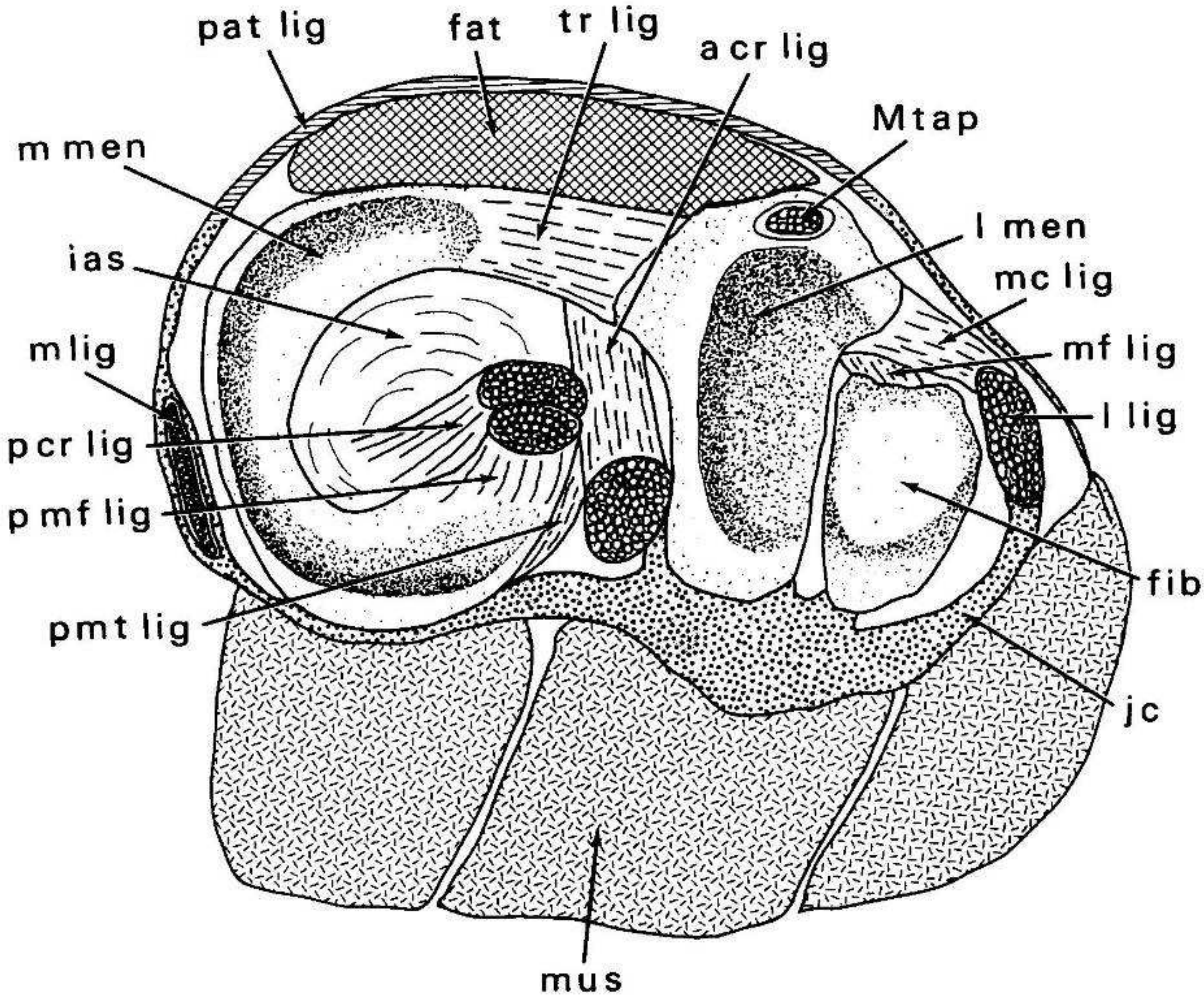


Figure 2: Schematic representation of the morphogenetic events in the formation of a synovial joint, indicating the source of synovial mesenchyme either (1) directly from limb mesenchyme (2) from blastema. (From: O' Rahilly and Gardner 1956)

In brief, according to O’ Rahilly and Gardner (1956) the development of the chicken knee starts 4½ - 5 days when the early cartilaginous blastema is segmented in three portions: the future fibula, tibia and femur. On the 6th day, ossification in the knee region is first observed, while after half a day the first cartilage phase is observed. The larger femorotibial interzone is close to blood vessels, and condensations for cruciate ligaments and medial meniscus are seen. At days 8-9, the embryonic knee is a miniature replica of the adult joint with the exemption of the patella, which at this stage is not yet defined by a distinct perichondrium. At day 11, the joint cavity is a continuous space, and the patella is already chondrified.

3.1.1 Macroscopic anatomy of the avian femorotibial joint

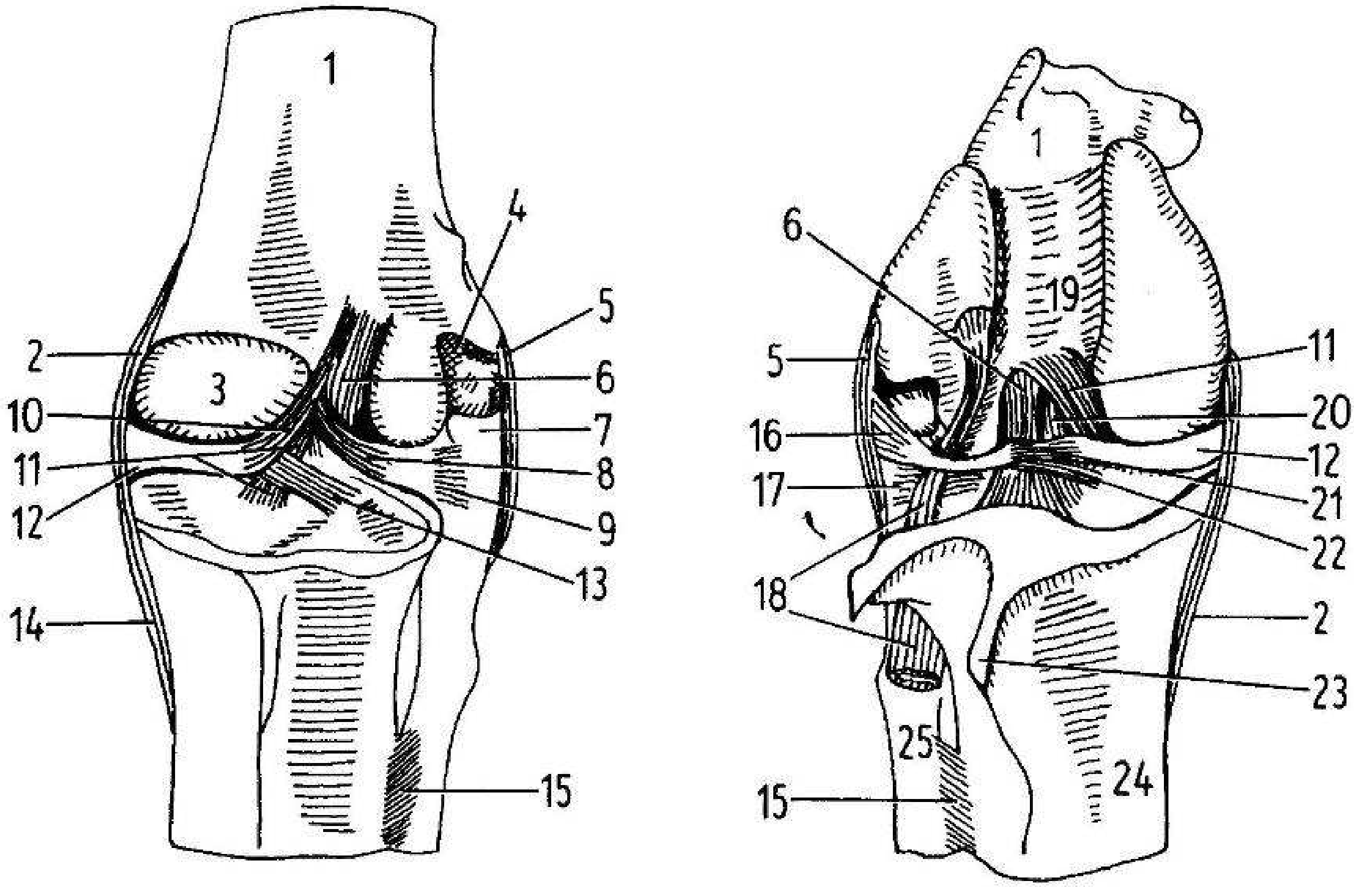
A depicted aspect of the avian femorotibial joint was presented in the mid ‘50s (O 'Rahilly and Gardner 1956), although earlier Haines (1942) and later Sonnenschein (1951) have described the chicken femorotibial joint in their comparative studies as well. A pioneer study of the macro- and microscopical anatomy, as well as its function, of the domestic pigeon was produced by Cracraft (1971) (see Fig. 3), while later Baumel (1978) revised the joint anatomical terminology and produced detailed drawings of the pigeon femorotibial joint (see Fig. 4). The latter texts were extensively used in modern atlases (Salomon 1993; Nickel et al. 1998; Hummel 2000; Maierl et al. 2001). A comparison of the femorotibial joint in various species, from an evolutionary perspective, included also the domestic chicken (Dye 1987). Studies during ‘80s and ‘90s focused on the detailed pathological role and depiction of the structural components of the avian femorotibial joint (ligaments, menisci, articular cartilage, and innervation) (mainly by Duff, SRI and Thorp, B.H). More recently a number of studies have described the femorotibial joint in various avian species (Cho et al. 1984; Fuss and Gasser 1992; Fuss 1996; Harcourt-Brown 2000; Wendt 2000; Wagner 2004).



A Schematic diagram of proximal end of tibiotarsus showing knee joint structures in *Columba livia.*

Abbreviations: a cr lig, anterior cruciate ligament; fat, fat pad; fib, fibula; ias, internal articular surface; jc, joint capsule; l men, lateral meniscus; mc lig, meniscocollateral ligament; mf lig, meniscofibular ligament; m lig, medial ligament; m men, medial meniscus; M tap, M. tibialis anterior, posterior slip; mus, muscle; pat lig, patellar ligament; p cr lig, posterior cruciate ligament; p mf lig, posterior meniscofemoral ligament; p mt lig, posterior meniscotibial ligament; tr lig, transverse ligament; l lig, lateral ligament.

Figure 3: Depiction of the pigeon stifle joint in transverse section by Cracraft. (Cracraft, 1971)



B. Pigeon right femorotibial joint. Caudal view (left) and cranial view (right). (after Baumel, 1979)

1 Femur
2 Ligamentum collaterale mediale
3 Condylus medialis
4 Trochlea fibularis
5 Ligamentum collaterale laterale
6 Ligamentum cruciatum craniale
7 Caput fibulae
8 Ligamentum menisco-femorale des lateralen Meniskus
9 Ligamentum menisco-fibulare caudale
10 Ligamentum menisco-femorale des medialen Meniskus
11 Ligamentum cruciatum caudale
12 Meniscus medialis
13 Ligamentum menisco-tibiale caudale
14 Ligamentum collaterale mediale
15 Ligamentum interosseum tibiofibulare
16 Ligamentum menisco-collaterale
17 Ligamentum tibiofibulare craniale
18 M. tibialis cranialis
19 Sulcus patellaris
20 tibiale Befestigung des Meniscus medialis
21 Ligamentum transversum genus
22 Ligamentum menisco-tibiale craniale
23 Crista cnemialis cranialis
24 Tibia
25 Fibula

Figure 4: Detailed anatomy of the pigeon femorotibial joint in boty views as depicted by Baumel 1978

3.1.1.1 Osteology

Four bones outline the avian femorotibial joint - the distal femur, the patella, the proximal tibiotarsus and the proximal fibula. Parts of these bones are intra-articular. The subchondral bone plays a major role in the stifle locomotion and disease pathogenesis and therefore emphasized in this chapter.

3.1.1.1.1 *Femur*

The **femur** is a strong tubular bone, which has the largest diameter in the pelvic limb (see Fig. 5). It slopes forward cranially in Galliformes, but may be fairly straight in

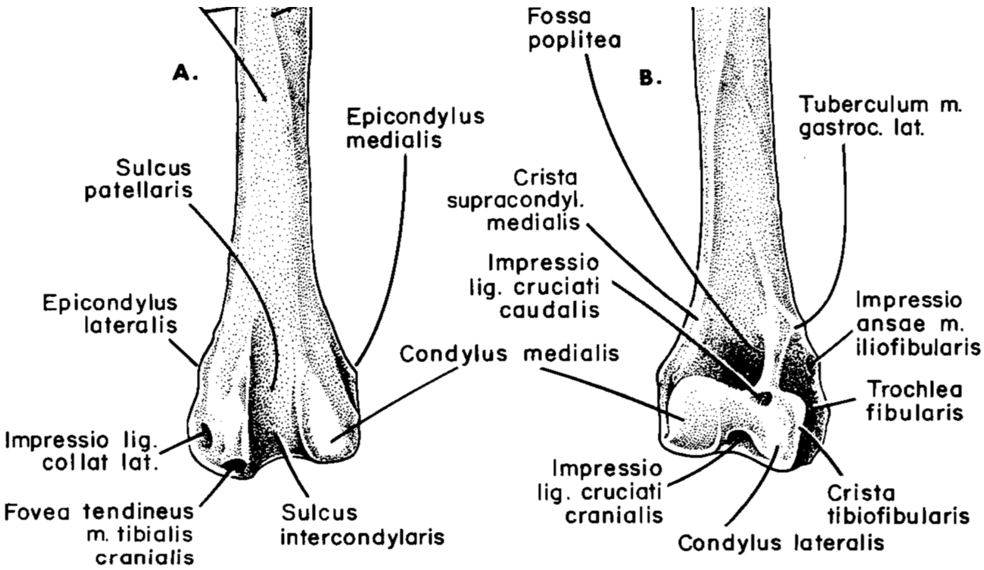


Figure 5: Cranial (A) and caudal (B) aspects of the right distal femur of a gull (Larus argentatus). (Adapted from Baumel 1993).

raptors (Harcourt-Brown 2000). On the other hand, the femur is remarkably short in ducks and geese, and is directed obliquely craniodistally and laterally in the standing position in these species (Nickel et al. 1998). Recent studies have dealt with the morphology and length of the femur and tibiotarsus, as well as their functional correlation with habitat use, in various species (Guillet 2003; Zeffer et al. 2003). The distal extremity of the femur is large (Nickel et al. 1998). The cranial surface is dominated by the *trochlea femoris/sulcus intercondylaris* which consist of two ridges separated by a groove. The latter contains also the *Sulcus patellaris* (Maierl et al. 2001). The ridges continue to two cylindrical, distocaudally directed condyles (*Condylus lateralis* and *medialis*). The lateral condyle extends further distally and is divided caudally into two ridges, of which the medial articulates with the tibia and the lateral with the fibula (*Trochlea fibularis*) (Nickel et al. 1998; Maierl et al. 2001). Proximal to the condyles the *Epicondyli lateralis* and *medialis* (Maierl et al. 2001) are located. The femur is pneumatised by connection with the abdominal air sac (Harcourt-Brown 2000).

3.1.1.1.2 Patella and patellar fat pad

The **patella** (knee cap) is present in most birds and is exceptionally large in waterfowl (King and McLelland 1984; Olsen et al. 2000). It is a small ovoid sesamoid bone, enclosed in the tendon of the *M. quadriceps femoris*, which glides in the patellar sulcus of the femoral trochlear (*Trochlea femoris*) (Cracraft 1971; Nickel et al. 1998). Caudally to the patella, an intraarticular fat body (infrapatellar fat pad) can be detected (*Corpus adiposum retropatellare*) (Baumel and Raikow 1993). In pigeons, this fat pad contains considerable amounts of fibrous matrix, which is strongly connected posterior to the cnemial crest, the joint capsule medially and laterally, the patellar and other ligaments and consequently the menisci. Proximally the fat pad extends till the patella (Cracraft 1971). Ratites lack a patella, but instead one or two osseous or fibrocartilaginous structures are present within the tendon of insertion of the femorotibialis muscle (Cho et al. 1984; Fowler 1991; Wagner 2004)

3.1.1.1.3 Tibiotarsus

The zeugopodium consists of the tibia and the fibula. The tibia is a strong tubular bone fused with the proximal row of tarsal bones (*Ossa tarsalia*) during the growth of the

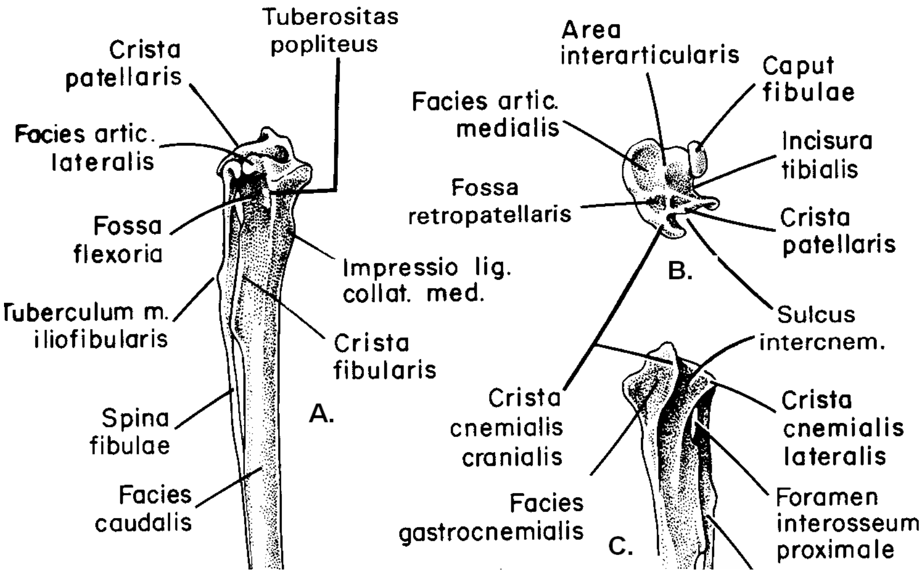


Figure 6: Cranial (A) and caudal (C) aspects of the left proximal tibiotarsus of a goose (Branta canadensis). In (B) the proximal articular surfaces are shown. (Adapted from Baumel 1993).

embryo, named thereafter **tibiotarsus** (see Fig. 6). In ducks and geese, the shortness of the femur is compensated by the long tibiotarsus (twice the femur length). In fowl and pigeons, the tibiotarsus is only by one third longer than the femur. In foot-propelled diving birds (loons and grebes) the tibiotarsus is elongated and parallel to the pelvic girdle (King and McLelland 1984). The proximal end of the tibia presents two facets, the small *Facies articularis lateralis* and the bigger *Facies articularis medialis,* which articulate with the femoral condyles. On the cranial face of the tibia, the *Crista cnemialis cranialis* starts, which on the proximal end connects with the *Crista patellaris*, where the *Lig. patellae* is attached. The *Crista cnemialis lateralis* is connected to the *Crista patellaris*. In grebes, the cnemial crest is fused to the patella, but not also in loons, which is just higly developed and prominent (King and McLelland 1984). Between the two cnemial acrolophies lies the *sulcus intercnemialis* where the *M. extensor digitorum longus* originates. The lateral surface of the lateral condyle also articulates with the head of the fibula (*Facies articularis fibularis*) (Maierl et al. 2001).

3.1.1.1.4 Fibula

The **fibula** has a prominent head (C*apitulum fibulae*), which articulates with the tibia (*Facies articularis tibialis*) and contacts the lateral condyle of the femur (*Facies articularis femoralis*). At some distance from the head, the needle-like, pointed, thin body of the fibula (*Spina fibulae*) forms a syndesmotic or synostotic junction with the distinct bony ledge of the tibiotarsus, which runs distally as a small narrow ledge on the lateral surface of the tibial trochlear. In most species the fibula runs along the two thirds of the tibiotarsus, with the exception of penguins and darters, in which it reaches the intertarsal joint (King and McLelland 1984). The fibula is attached to the tibiotarsus at the fibular crest (*Crista fibularis*) and not at the most proximal portion of the bones (as in mammals). The lateral collateral and femorofibular ligaments also retain contact of the fibula with the femur.

3.1.1.1.5 Subchondral bone

The **subchondral bone** and *epiphyseal bone* provide structural stability to the overlying articular cartilage, and variations in their stiffness may result in articular cartilage injury (Radin and Rose 1986). These integral parts of the joint remodel in response to changes in load, while their cells play a role in self-repair after osteochondral fractures. Much of the rebound energy generated by weight-bearing movement is attenuated by soft-tissues, but load must also be borne by the bone. The stiffness and rigidity of the bone lies upon its 65% mineral content: the *hydroxyapatite* (Boskey 1981). The remaining 35% (of which 25% is water) is composed of 95% type I collagen and 5% proteoglycans. The uncalcified extracellular matrix is called *osteoid* and the main type of cell in the bone, the osteoblasts, produces it. In general, the subchondral bone is a mixture of trabecular and osteonic bone, whereas the epiphyseal bone is trabecular. The significant difference is that trabecular bone may be 50-90% porous, in contrast with cortical bone, which is less than 30% porous, influencing their mechanical properties (Todhunter 1996). The avian femoral trabecular bone is critical for resisting impact loads and also sensitive to changes in load orientation (Pontzer et al. 2006; Reich and Gefen 2006)

3.1.1.2 Articular cartilage

The cartilage covering the part of the epiphysis, which articulates with an apposing bone to form a joint, is referred as **articular cartilage**. In mammals, the articular cartilage can be semitransparent (hyaline), smooth and blue-white, due to its high water content (70% in adult horses) (see also Fig 7). On a dry weight basis, it

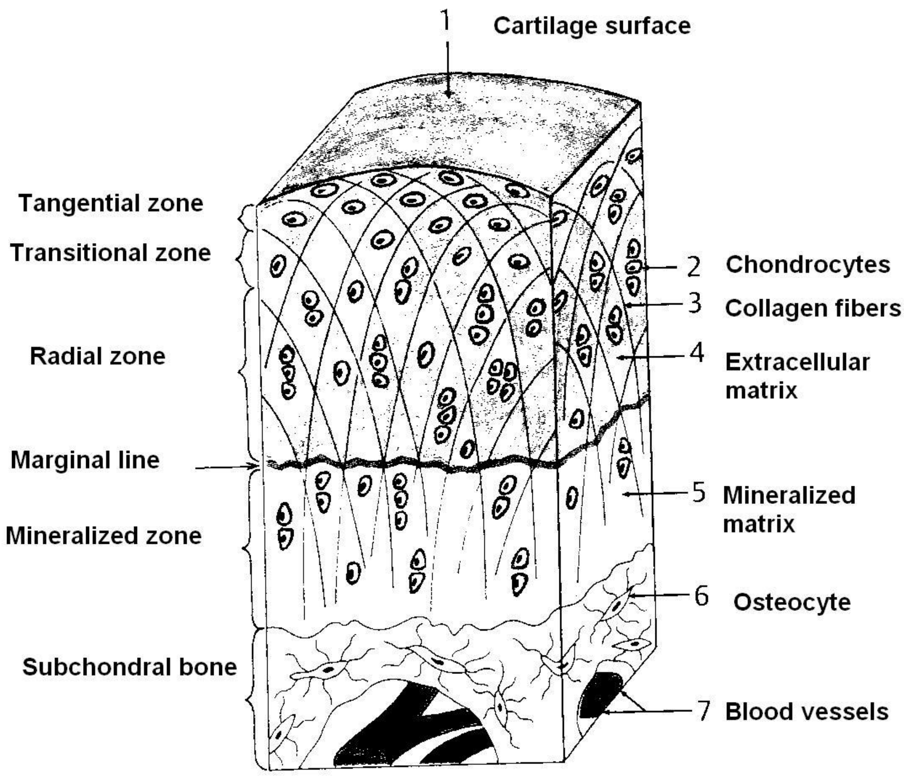


Figure 7: Schematic structure of the mammalian articular cartilage (adapted by (Salomon et al. 2005)

contains 50% collagen, 35% proteoglycan, 10% glycoproteins, 3% mineral and 1% lipid (Todhunter 1996). According to Duff (1987b), the avian joint surface contains fibrocartilage, rather than hyaline cartilage. Additionally, Gardner and McGillivray (1971) studied the articular cartilage of the knee joint (femoral condylar, patellar, upper tibial) of the turkey, identifying several differences to mammals. In the femoral condylar cartilage, a network of blood vessels lay under the small surface (20µm-40µm), which penetrate the cartilage, forming a pattern of irregularities. A pattern of longitudinal and cross bands, of similar diameter with their surfaces, overlaid by 20 to 40 µm tertiary undulations was also detected. According to the same authors, careful observation revealed parallel bands (wear lines) ranging in colour from grey to white, suggesting the presence of collagen and giving the impression of more deep surfacial ridges (Gardner and McGillivray 1971). Closing, Cracraft (1971) described microscopically the articular cartilage in the knee joint of the domestic pigeon.

3.1.1.3 Articular (joint) capsule, synovial membrane and synovial fluid

The **joint capsule** consists of a thick fibrous portion, which is lined by a thin *subsynovium* (lamina propria) and the *synovium* (synovial membrane), which comes in contact with the synovial fluid. The collateral ligaments are intracapsular, while the intraarticular ligaments (i.e cruciates) are extrasynovial. In healthy joints, a small volume of synovial fluid occupies the intraarticular space. The joint capsule consists mostly of connective tissue and is of low cellularity (Todhunter 1996; Campbell and Ellis 2007). A detailed description of the pigeon knee joint capsule (macroscopical and microscopical) was given by Cracraft (1971). Finally, the capsule is well innervated by free nerve endings and therefore regarded as an important source of pain in osteoarthritis (Caron 1996). In birds, the joint capsule is constructed (thicker parts) to resist to lateromedial swing, translation and rotation and provide stability and motion limitation, especially when muscles fail to respond (Cracraft 1971)

The **synovium** is modified mesenchyme. The intima overlies a layer of connective tissue (lamina propria), which may be fibrous, areolar or adipose. The intima is one to four synoviocytes thick. Synovial lining cells synthesize hyaluronan, which is secreted into the synovial fluid. Lubricin (a surface acting glycoprotein) is involved in the boundary lubrication of cartilage and is probably synthesized by the synovium (Henderson and Pettipher 1985). Despite the fact, that the synovium itself is mechanically weak and has no known biomechanical role, it is recognised that synovial injury may have consequences in the pathophysiology of the joint (Evans 1992). High intraarticular pressure (e.g. flexion of a joint with sufficient synovial effusion) could impair the blood flow of the synovial capillaries. Injury and inflammation to the membrane, causes pain, direct release of lysosomal enzymes, prostaglandin E_2, free radicals and cytokines (Platt 1996).

The **synovial fluid** is an ultrafiltrate of plasma and contains high proportions of hyaluronan. Hyaluronan is the only glycosaminoglycan that is not sulphated, does not have protein core and gives the normal synovial fluid its viscous appearance (Todhunter 1996). Fluid exchange between plasma and synovial fluid happens through hydraulic, hydrostatic and colloid pressure differences (Levick 1984). The fluid acts as the medium trough which the nutrients reach the intraarticular components (cartilage, ligaments) (Amiel et al. 1986). Additionally, the intrasynovial pressure is subatmospheric (-2 to -6cm H_2O) (Knox et al. 1988), which may assist in stabilising the joint. The avian synovial fluid consists mainly of mucopolysaccharides (hyaluronic acid), macrophages, few leukocytes and synovial lining cells. Change of its viscosity and cytology may indicate septic or traumatic arthritis, articular gout or erosion of the articular cartilage (Campbell and Ellis 2007). Recently, Corr et al. (2003) studied the synovial fluid in poultry as a joint disease indicator. It was found, that in healthy joints its colour was similar to mammalian fluid (clear, pale yellow), its volume (0.2-0.85 ml) is relatively higher than in mammals of even bigger size, and its alkalinity (pH 8.4) is also higher, a fact that may explain the avian susceptibility to urate arthritis.

3.1.1.4 Ligaments and menisci

The avian femorotibial joint contains possibly more ligaments than that of any other vertebrate (Haines 1942; Cracraft 1971). It is widely accepted that the avian stifle comprises by the following four separate articulations whose synovial cavities intercommunicate: the *Articulatio femorotibialis,* the *Articulatio femoropatellaris,* the *Articulatio femorofibularis and* the *Articulatio tibiofibularis* (Baumel and Raikow 1993; Salomon 1993; Nickel et al. 1998; Maierl et al. 2001).

The first, which is considered as the main femorotibial joint, is incongruent and filled with the help of the **lateral and medial menisci**, which are load-bearing structures.

Their main roles are (i) increase of stability (ii) even weight distribution and (iii) facilitation of rotational movements (Cracraft 1971). The medial meniscus is C-shaped with a cranial and caudal horn. In the pigeon, the outer edge is thicker than the inner, giving it a triangular shape in cross section (Cracraft 1971). The horns come in direct contact with the *Os femoris* and the tibia, to which they are attached with the help of the following ligaments: *Lig. meniscotibiale caudale, Lig. meniscofemorale and Lig. transversum genu*s (Salomon 1993). The latter connects the two menisci cranially. The open central part of the medial meniscus allows direct contact of the medial femoral condyle with the tibiotarsus (Baumel and Raikow 1993). Medially and caudally, the meniscus is joined to the capsule (Cracraft 1971). In birds the lateral meniscus is rectangular and oblong rather than crescentic as in mammals (Duff 1987a). It is attached at its distal end to the interarticular area of the tibial head, while laterally is affixed to the inner surface of the *Caput fibulare*. On the cranial surface there is an indentation, over which the tendon of the *M. tibialis cranialis* passes. The lateral meniscus is attached to the tibia with the *Lig. meniscotibiale craniale*, to the fibula with the *Lig. meniscofibulare caudale and craniale* (Fuss 1996), while the *Lig. meniscocolateralle* connects its cranial periphery with the cranial border of the *Lig. collaterale laterale* (Haines 1942; Cracraft 1971). Finally, the *Lig. meniscofemorale* is directed towards the medial femoral condyle (Salomon 1993; Maierl et al. 2001)

The cruciate ligaments (cranial and caudal) are at the centre of the *Articulatio femorotibialis* and, together with the collateral bands (medial and lateral) in the periphery, guarantee the stability of the joint and prevent excessive rotational or linear motion. Besides morphological descriptions of these ligaments, in domestic fowl and pigeon (Haines 1942; Sonnenschein 1951; O 'Rahilly and Gardner 1956; Cracraft 1971; Baumel 1978; Dye 1987) more targeted studies on the morphology, function and pathology of the ligaments have been published (Duff 1985; Duff 1986a; Duff 1986b; Duff 1988), including also other avian species (Fuss and Gasser 1992; Harcourt-Brown 2000).

According to Fuss and Gasser (1992) no morphological differences were found in the location and fiber arrangement of cruciate ligaments in the species examined (*Gallus, Anas, Meleagris* and *Struthio*). Generally, the femoral attachment of the **caudal**

cruciate ligament was found to be in the intercondylar groove, and after following an oblique path, inserts posteriorly at the medial tibial condyle. In the pigeon, this latter attachment is broad, while overall the ligament is thick and strong in its lateral edge and flattened medially (Cracraft 1971). The femoral attachment of the **cranial cruciate ligament** was situated at the lateral femoral condyle in most species (Cracraft 1971; Fuss and Gasser 1992; Harcourt-Brown 2000), except in the ostrich where it lies intercondylary (Fuss and Gasser 1992) (see also Fig. 8). The cranial cruciate ligament runs in the sagittal plane and is roughly attached to the centre of the tibial plateau. In the pigeon, it is flattened at its ends and rounded in the centre (Cracraft 1971). An accessory fiber bundle in the cranial cruciate was detected in one case of a turkey only. Interestingly, both cruciates are deflected around the intercondylar groove (cranial) and the medial femoral condyle (caudal) (Fuss and Gasser 1992). Here it would be of some importance to underline that a ligament of Wrisberg analogue, which is present in mammals and reptiles (the latter class having three or four cruciates according to Haines (1942) and Wink (1989)) was not found in birds (Dye 1987). The cruciate ligaments consist of collagenous ligament tissue, fibrocartilage and hyaline cartilage. These different tissues are irregularly distributed in the ligaments of the ostrich, but showing a characteristic pattern in the chicken (Fuss and Gasser 1992).

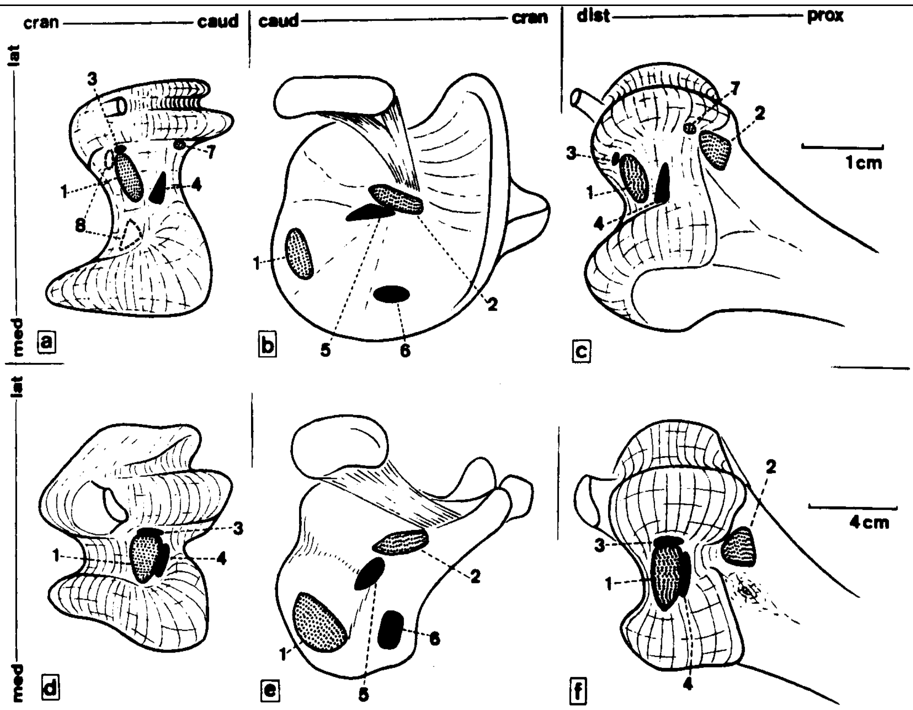


Figure 8: Shape and location of cruciate (stippled) and meniscal ligaments (solid) in turkey (upper) and ostrich (lower). (a,d): Distal femur. (b,e): Proximal tibia. (c,f): Caudal femur, 1. caudal cruciate, 2. cranial cruciate, 3. cr. meniscofemoral, 4. caud. meniscofemoral, 5. caud. meniscotibial, 6. cr. meniscotibial, 7. accessory bundle of the cr. cruciate, 8. transverse band crossing the intercondylar groove. (Adapted from Fuss and Gasser 1992). Note in (d,f) the intercondylary cranial cruciate femoral attachment, found only in the ostrich

The collateral ligaments exhibit also structural and morphological uniformity among avian species. The **medial collateral ligament** is attached to the medial femoral condyle and runs to the medial side of the tibiotarsus. It is widest at the level of the articular surfaces and attached to the medial meniscus, forming a bursa. In the goshawk (*Accipiter gentilis*) and Falcomiformes it is reinforced by an accessory band (Harcourt-Brown 2000). The **lateral collateral ligament** runs from the proximal end of the fibular head to the lateral side of the lateral femoral condyle. The attachment to the femoral condyle is large and extends proximally onto the lateral femoral shaft (Cracraft 1971). Exceptionally, in the Goshawk (*Accipiter gentilis*), there is no accessory band, as there is in the peregrine falcon (*Falco peregrinus*) (Harcourt-Brown 2000). Duff (1986b) and Cracraft (1971) have produced drawings of these attachments in the broiler fowl and the pigeon, respectively (Fig. 9).

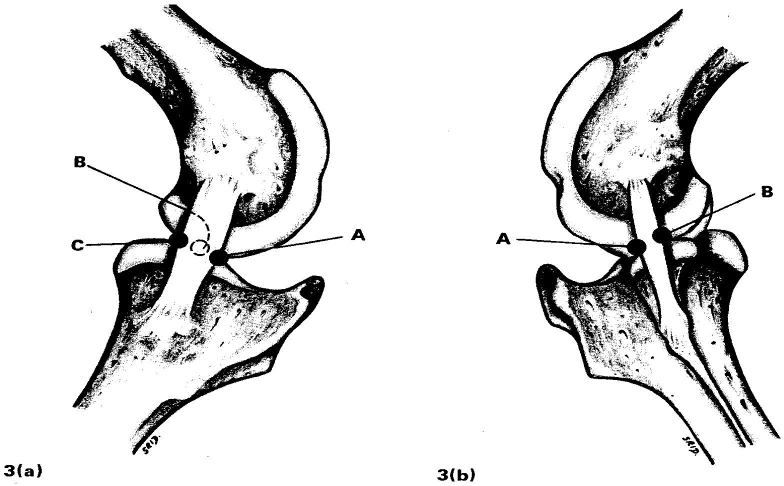


Figure 9: Attachments and frequent rupture sites of the collateral ligaments of the broiler fowl. 3(a): Medical aspect: A=cranial border, B=mesial point, C=caudal point. 3(b): Lateral aspect: A=cranial border, B=caudal border (modified from Duff 1986b).

In the *Articulatio femoropatellaris*, the patella articulates with the *Facies articularis patellaris* of the distal femur. The patellar ligament (*Lig. patellae*) represents the extension of the tendon of the *Mm. femorotibialis* that links the distal patella to the *Crista patellaris* of the tibiotarsus. This ligament represents much of the cranial wall of the articular cavity of the *Art. femorotibialis* (Baumel and Raikow 1993).

The femorofibular articulation (*Articulatio femorofibularis*) is formed between the proximal and medial articular facets of the fibular head with the *Trochlea fibularis* of the lateral femoral condyle. In two raptor species (goshawk and peregrine falcon), the head of the fibula is not attached to the tibiotarsus and therefore allows some rotational movement at this joint. The amount of rotation was similar in all the Falconiformes that were examined (Harcourt-Brown 2000).

Finally, the *Articulatio tibiofibularis* is a diarthrosis at its proximal end, while forming a synarthrosis distally (Maierl et al. 2001). The *Caput fibulae articulates* directly with the lateral surface of the tibiotarsus just distal to the point of attachment of the lateral meniscus to the *Caput fibulae* on the lateral and to the tibial plateau on the medial side. At this level the two bones are fastened together by two ligaments: the extracapsular *Lig. tibiofibulare obliquum (Meleagris, Ghetie, 1976, Columba, Baumel, 1993)* and the almost tranverse, intracapsular *Lig. tibiofibulare craniale*, which is located beneath the *Lig. transversum genus* (Baumel and Raikow 1993; Harcourt-Brown 2000). The *Lig. interosseum tibiofibulare*, is slightly movable and connects the *Crista fibularis* with the *Corpus fibulae* and the *Spina fibulae*. In ostrich, the tibiofibular junction consists of the *Lig. tibiofibularia caudale, craniale proximale* and *distale, obliquum* and *interosseum* (Fuss 1996). In contrast to the Nomina Anatomica Avium, the author argues that the tibiofibular junction is a synovial joint (*Articulatio*) for the following reasons: (a) a motion of 35 ^{o} of the fibula cannot be regarded as minimal, (b) the supposed articulated surfaces do not present cartilaginous cover, and (c) this junction (in ostrich) does not exhibit free mobility in its range of motion. Therefore, the most appropriate nomenclature for the entire tibiofibular junction would be “syndesmosis” (Fuss 1996).

3.1.1.5 Vascularisation

The structures of the femorotibiotarsal joint are provided with nutrients by a complex system of vein and arteries, which arise from the *A. ischiadica* and *A. iliaca externa.* In most species the *A. ischiadica* becomes the *A. poplitea* after giving off the *A. suralis*, which divides into the *A. suralis lateralis and medialis* branches. The *A. poplitea* then gives off branches, which are the *A. genicularis lateralis* and *medialis* (Baumel 1993; Harcourt-Brown 2000; Krafczyk 2001; Ruberte et al. 2001). The former are progressing to *A. epicondylaris lateralis* and *medialis* (Baumel 1993).The medial knee arteries anastomose with the *A. femoralis medialis* to the *A. iliaca externa* (Wendt 2000). The *A. poplitea* furthermore divides in the *A. tibialis caudalis* and the *A. tibialis medialis*. Distal *to the A. tibialis caudalis* the artery branches to form *the A. fibularis and the A. tibialis caudalis*. The *A. fibularis* passes between the tibiotarsus and the fibula proximal to the fibula crest. It runs on the cranial aspect of the fibular crest and then divides directly into deep and superficial branches (see also Fig. 10) The vascular pattern of the knee joint in developing fowl has been further investigated by Thorp (1988b; 1988a; Thorp and Duff 1988). According to his finding, the cartilaginous epiphysis contains epiphyseal vascular canals (EVCs), which terminate either in the physis as penetrating epiphyseal canals or in the epiphyseal hyaline cartilage as blind entering capillary loops. A branch of the medial femoral artery from the medial epicondyle crosses the cranial surface of the distal femur to spread branches on the trochlea, which gives rise to retinacular vessels, contributing to the vascular supply of the cruciate ligaments. Additionally, a branch of the *A.*

poplitea on the distocaudal femoral aspect penetrates the intercondylar cartilage. This vessel radiates to form a horseshoe-like shape of six EVCs, which provides the main blood supply to the epiphysis (see also Fig 10). Regarding the cranial proximal epiphyseal tibiotarsus, this is covered by a network of extracapsular retinacular vessels. Moreover, a large vessel, originating from the joint capsule between fibula and lateral cnemial crest, runs intra-articularly to enter the cartilaginous epiphysis on the craniolateral intercondylar eminence and further radiates EVCs. This vascular pattern shows similarities with reported patters of other species (Thorp 1988b).

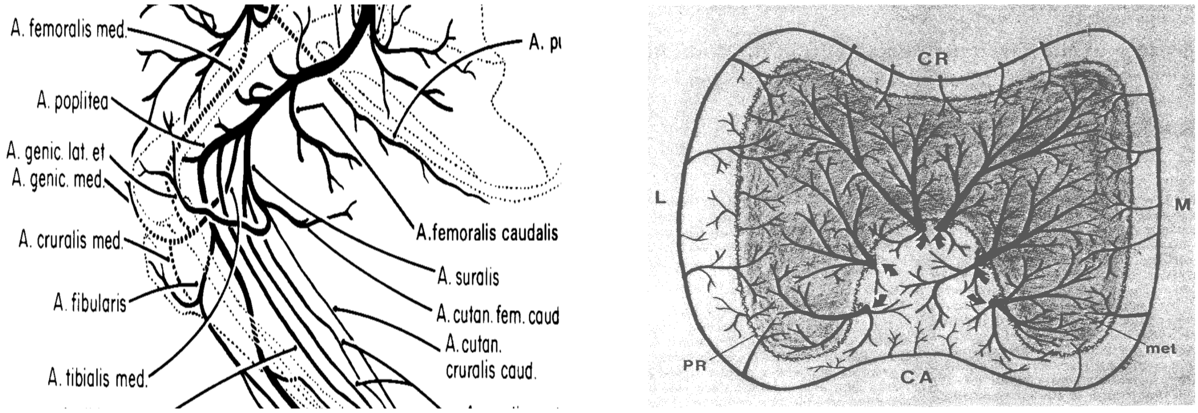


Figure 10: The gross vascularisation of the left lateral knee joint of a pigeon (from BAUMEL 1993) and the micro-vascularisation of the distal femoral epiphysis in a transverse section in a chicken (Adapted from Thorp 1988b).

The main venous return comes through the femoral vein (*V. femoralis*). In the pigeon (*Columba livia*) and the chicken (*Gallus gallus*), the *V. ischiadica* is a separate entity with an anastomosis that runs from the *V. ischiadica* to the *V. femoralis,* which then carries the majority of the venous return from the limb. The main vein of the tibiotarsal region is the *V. tibialis caudalis*, which drains into the *V. poplitea* (Harcourt-Brown 2000; Wendt 2000). The knee veins *V. genicularis lateralis* and *medialis* also direct blood into the *V. poplitea* (Baumel 1993).

3.1.1.6 Innervation

The pelvic limb of all birds is innervated by nerves that arise from the lumbosacral plexus. Small branches from the autonomic nerves also join the plexus. The lumbosacral plexus forms three nerve trunks that supply the limb: the femoral nerve, the obturator nerve, and the ischiadic nerve, which is also the most prominent (Dubbeldam 1993; Harcourt-Brown 2000; König et al. 2001; Krafczyk 2001). The femoral nerve supplies the extensors of the femorotibial joint (Harcourt-Brown 2000), playing an integral part in the myotatic patellar reflex. The independent articular branches of peripheral nerves and muscle nerves control proprioception and help to restrict motion to the physiologic range. The nerves accompany the blood vessels into the synovial tissues, ending in the joint capsule, fat pad, ligaments and menisci (Todhunter 1996). In the case of birds, branches of *N. femoralis*, *N. fibularis*, *N. tibialis* and/or *N. paraperoneus* should supply the femorotibial joint, although this is not clearly illustrated in any anatomical atlas.

The sensory innervation of the joint is important, as it largely contributes to motion, nociception and joint pain (Caron 1996). According to Malinovsky and Zemanek (1970), the first study of joint sensory innervation in domestic fowl (*Gallus domesticus*) was conducted by Rauber (1867), but a detailed paper on sensory corpuscles in the avian joint capsule published far later by Polacek et al. (1966). The main finding was the variability - from typical Herbst's corpuscles to simple corpuscles similar to the mammalian ones. The same year, Polacek (1966) described the sensory joint corpuscles of the pigeon, and later Sklenska described them in domestic duck, teal and pochard (Sklenska 1967; Sklenska 1969; Sklenska 1971; Sklenska and Janska 1972). Later, Halata and Munger (1980) studied the ultrastructure of Ruffini and Herbst corpuscles in the shoulder joint capsule of the domestic pigeon, and recently Palmieri et al. (2005) described the autonomic and sensitive somatic innervation of the ostrich elbow and knee joint articular capsules.

In general, it was noted that a greater abundance of joint receptors exists in birds than in mammals, and in comparison to the latter, the maximum number of receptors (at least in duck species) is located in the wing joint capsules (Malinovsky and Zemanek 1970; Sklenska and Janska 1972). By constrast, the rook and the domestic hen show a significant shift of the innervation focus towards the legs, assuming that the number of receptors is greater in the joint capsules of the limbs which are more intesively functional or perform movements which require preciseness (Malinovsky and Zemanek 1970). Encapsulated corpuscles, free nerve and spray–like endings (Ruffini corpuscles) were observed in all referred studies. The free nerve endings and spray-like endings were rare, located only in the wing joints, and same as in mammalian joint (Sklenska and Janska 1972; Halata and Munger 1980). In the pigeon shoulder joint capsule, Ruffini corpuscles occurred only in the fibrous membrane, while Herbst corpuscles occurred also in the subsynovial connective tissue and in the transition zone between fibrous membrane and muscular fascia. There are two types of Herbst corpuscles in the articular capsules of domestic pigeon. The Ruffini corpuscles have similar function to the mammalian receptors, being sensitive to changes in intra-joint pressure and capsule tension, and thus may monitor the relative positions of the bones (Halata and Munger 1980). In the ostrich, the autonomic innervation was represented by few isolated or grouped ganglion cells along the nerve trunks within the perineural connective tissue, whilst the sensitive somatic innervation was represented by free endings and encapsulated corpuscles (Pacini, Pacini-like and Golgi-Mazzoni's). The few Golgi-Mazzoni's corpuscles were found in the knee joint articular capsule (Palmieri et al. 2005).

3.1.2 Diagnostic imaging of the avian femorotibial joint

Diagnostic Imaging is a principal tool for diagnosing femorotibial joint diseases. Main indications for stifle imaging are pain detection upon examination of the joint or the surrounding bones, joint/soft tissue swelling, positive cranial drawer or tibial compression test and finally assessment of growth deformities (Comerford 2006). The basic examination is the radiographic one. Other advanced methods, used in small animal practice, are ultrasonography, scintigraphy, computed tomography (CT) and magnetic resonance imaging (MRI). These are yet under trial and not routinely performed in the avian practice.

3.1.2.1 Radiographic anatomy and conventional radiology

Normal and abnormal avian radiographic anatomy has been described by many authors using normal and xeroradiographic techniques in the most common presented avian species (Rubel et al. 1991; Smith and Smith 1992; McMillan 1994; Smith and Smith 1997; Harcourt-Brown 2000; Samour and Naldo 2007). In these textbooks the femorotibial joint is usually depicted as part of the whole extremity, while few of them refer separately to the avian femorotibial joint (Harcourt-Brown 2000). According to Harcourt-Brown (2000), the best visualization of the joint could be achieved with a mediolateral and a caudocranial projection. Zinc oxide tape and sandbags are useful to prevent rotation of the leg along its long axis. Craniocaudal projections may have to be taken in some distance of the cassette and this may result in detail loss. A normal goshawk´s left femorotibial joint as produced by Harcourt-Brown (2000) depicts the basic visible joint structures (Fig. 11).

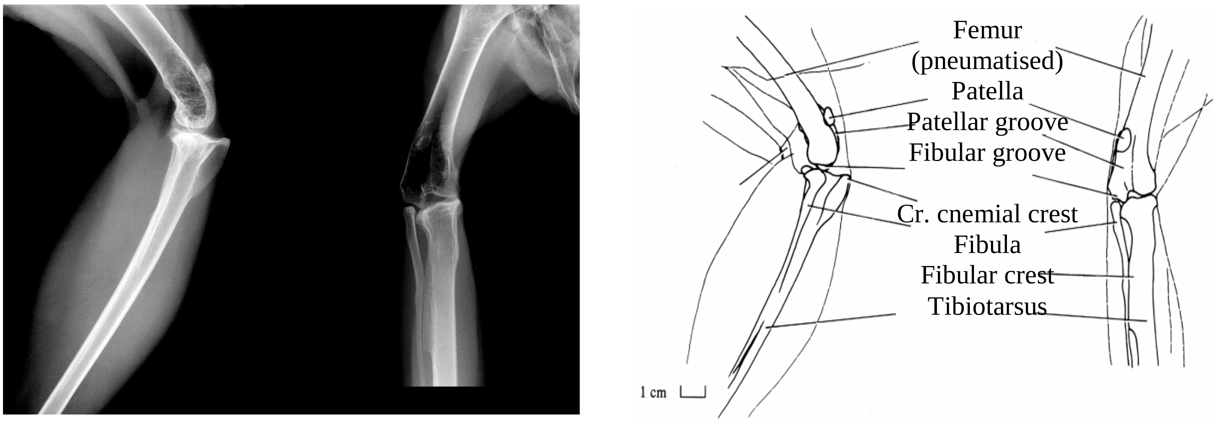


Figure 11: Mediolateral (left) and caudocranial (right) view of normal left goshawk (*Accipiter gentilis*) femorotibial joint with visualisation of the main bony structures (Adopted from Harcourt-Brown, 2000).

Magnification of radiographic images may prove helpful for interpretation. In the mammalian stifle joint, details that can be derived from plain radiographs include information on the size, contour, density, and location of changes that are present in or around a joint. The areas that can be evaluated include the subchondral bone plate, trabecular subchondral bone, articular margins, and areas where ligaments, tendons, and the joint capsule attach. Other projections, which could be applied, in avian patients of a reasonable size, are the craniodistal-cranioproximal view of the patella and stressed views to establish spatial derangements. The fact that a two-dimensional display of three-dimensional structures could obscure important findings is considered the main disadvantage of radiography (van Bree 2006).

3.1.2.2 Ultrasonography

Ultrasonography has not yet been attempted to facilitate diagnosis of avian femorotibial joint diseases under clinical conditions. Mutalib et al (1996) assessed sonographically osteomyelitis in commercial turkey femorotibial joint with a 78 % sensitivity rate, while Linn et al (2003) evaluated the use of ultrasonography to detect pathological conditions of intertarsal joint in sandhill cranes (*Grus canadensis*). The use of linear high-frequency transducers with 6.5 MHz and 7, 5 MHz probes are more commonly used in avian medicine. The small size of the joint structure and the lack of normal reference values prohibit the potential benefit of identifying soft-tissue damages (such as ligament rupture, meniscal tear or degeneration, synovial fluid, articular capsule and joint surfaces) as proposed in small animals (Comerford 2006; Marinou 2006; van Bree 2006).

3.1.2.3 Computed tomography (CT) and magnetic resonance imaging (MRI)

In small animal stifle diagnostics the MRI is usually applied for medial meniscal and cranial cruciate tears, while CT for long digital extensor tendon avulsion and patellar luxation management planning (Comerford 2006; van Bree 2006). Computed tomography has the advantage of cross-sectional anatomy and provides images with high quality. Nevertheless, even the 2 mm scanning slices may miss an area of interest, while the high rate of respiratory movements of avian patient, necessitate a procedure under general anesthesia (Rosenthal 2002). Moreover, provision of 3D reconstructions, following technologic improvements in scanning slices < 1mm, is nowadays possible. The MRI has the advantages of multiplanar imaging, soft tissue contrast, and non-invasiveness, but the available data in avian medicine is still limited (van Bree 2006; Samour and Naldo 2007).

3.2 Physiology, biomechanics and kinematics of the avian femorotibial joint

Although a detailed description of the avian femorotibial joint physiology and kinematics is beyond the scope of this study, it is important to roughly understand the main principles and differences between the avian and mammalian femorotibial joint, as often the clinical techniques (surgery, physical therapy) for the latter are extrapolated and applied to avian patients. Moreover, the possible functional differences could influence the therapeutical outcome.

Avian bipedalism, and its possible use as a model in human stifle joint research, was the motive for the first comparative studies. The main morphological and functional differences are summarized in Table 1 as identified by numerous authors (Cracraft 1971; Dye 1987; Arnoczky 1988; Robins 1990; Fuss and Gasser 1992; Carpenter and Cooper 2000b; Vasseur 2003)

Table 1: Comparative evaluation of femorotibial joint characteristics

Characteristics	Mammals	Birds
A. Osseous		
Femorofibular junction	No	Yes
Bone Epiphyses	Osseous intercondylar fossa	Covered by articular cartilage
Sesamoids (except patella)	Yes (2-3)	No
B. Soft-tissue		
Posterior meniscofemoral ligament	Yes	No
Popliteal insertion on the lateral femoral condyle	Yes	No
Patellar-Fabellae synovial pouch and sub-pouches	Yes	Not described
Percentage distance variation of cruciate attachments	Caudal cruciate: 30% Cranial cruciate: 60-70%	Caudal cruciate: 12% Cranial cruciate: 7%
Insertion of caudal cruciate ligament	Intercondylary	Medial tibial condyle
C. Functional		
Cruciate ligament fibre groups	Two	Four
Cruciate fibres, when taut	Rectilinear path	Deviation
Tension in cruciate fibres	No	Cruciate fibres relaxed in both extreme positions and taut in intermediate
Flexion-extension axis	Transverse	Longitudinal
Medial rotation of tibia in flexion	20-45^{o}	Min 50-60^{o}

3.2.1 Motion in the avian femorotibial joint

According to Cracraft (1971), the avian (pigeon as model) femorotibial joint can perform four types of motion: (a) Flexion-extension (b) Lateral-medial rotation (c) Lateral- medial swing (abduction/adduction of tibiotarsus) and (d) translation (sliding). The latter is the least important and practically absent or hardly noticeable in flexion. Flexion-extension is a combination of rolling and anteroposterior translation, taking place along the longitudinal axes of the bones. Pure rolling occurs only partially during the flexion-extension cycle. As lateral-medial rotation is defined as the spin of the femur along its longitudinal axis, while the lateral-medial swing takes place along the longitudinal axes in a lateromedial direction. Rotation becomes possible when the joint is flexed. In a flexed femorotibial joint of a common buzzard (*Buteo buteo*), the tibiotarsus was able to rotate at least 60^{o}, when the femur was stabilised (Harcourt-Brown 2000), and 50^{o} in pigeons (Cracraft 1971). The bones, the intra-articular ligaments, the lateral meniscus, the tibiofibular ligament, the collateral ligaments and finally the joint capsule, as well as the periarticular muscles prevent rotation during extension and flexion. The freedom of movement of the head of the fibula, and the movable attachment of the lateral collateral ligament to the fibula, allow the tibiotarsus to operate independently in the femorotibial joint, and permit an extra degree of rotation and medial swing of the joint around its long axis not seen in mammals (Cracraft 1971; Fuss 1996; Harcourt-Brown 2000). Maximal extension in the pigeon could be around 160^{o}, while in flexion the two bones can reach a parallel plain or even slightly overlap each other. Knee flexion is a key component in limb retraction (Cracraft 1971; Reilly 2000). In the running ostrich, the maximum of knee flexion/extension value occurs during the swing phase (Rubenson et al. 2007). The main muscles that flex the joint are the *M. biceps femoris*, the *M. semimembranosus* and the *M. semitendinosus*, and the relaxation of the *M. femorotibialis* contributes in some stages. The *M. gastrocnemius lateralis* contributes also to flexion. Furthermore, the *M. iliotibialis cranialis*, after cessation of action of the *M. iliofibularis*, protracts the knee, while the *M. femorotibialis* extends the tibiotarsus. Hyperextension is prevented by hamstring muscles (*Pars pelvica* of the *M. flexor cruris lateralis*, *M. flexor cruris lateralis*, and *M. iliofibularis*). The *M. iliotibialis cranialis* and the *Pars preacetabularis* of the *M. iliotibialis lateralis* have also extensor moments in the knee. The *M. popliteus* resists the forward velocity of the fibula as the joint extends (Cracraft 1971; Fuss 1996; Gatesy 1999a). Finally, the action of each ligament during the flexion-extension cycle of the pigeon have been described in detail by Cracraft (Cracraft 1971), while the functional role of the cruciate ligament system has been addressed by few authors (Duff 1986a; Fuss and Gasser 1992).

3.2.2 Gait and kinematic analysis of the avian pelvic limb locomotion, focusing on the avian femorotibial joint.

Gait and kinematical studies have been recently carried out in various avian species such as chicken (Reiter and Bessei 1997; Corr et al. 1998), pigeon (Cracraft 1971; Fujita 2004), starling (Earls 2000; Fujita 2004), corvids (Hayes and Alexander 1983; Verstappen et al. 2000), waterfowl (Abourachid 2001; Fujita 2004), turkey (Abourachid 1993; Roberts and Scales 2004), herons (Fujita 2004), quail (Earls 2000; Reilly 2000; Abourachid 2001; Alexander 2004), guinea fowl (Gatesy 1999b; Gatesy 1999a; Abourachid 2001; Pontzer et al. 2006), tinamou (Hancock et al. 2007) and ratites (Abourachid and Renous 2000; Abourachid 2001; Alexander 2004; Rubenson et al. 2007).

In general the avian gait can be divided into a stance phase (further consisting of a yield and propulsion phase) and a swing (or recovery) phase (with a flexion and extension phase) (Gatesy 1999b; Abourachid and Renous 2000; Fujita 2004; Rubenson et al. 2007) (see Fig. 12A). In Annex II, the femorotibial joint's flexion–extension angle in various species and gaits is listed. Since the femorotibial joint is hidden by the wings in most species, an alternative functional measurement is the hip-digit III or so-called total limb excursion angle (divided in protraction and retraction angles, see also Fig. 12B). The pattern of the movement of the femorotibial

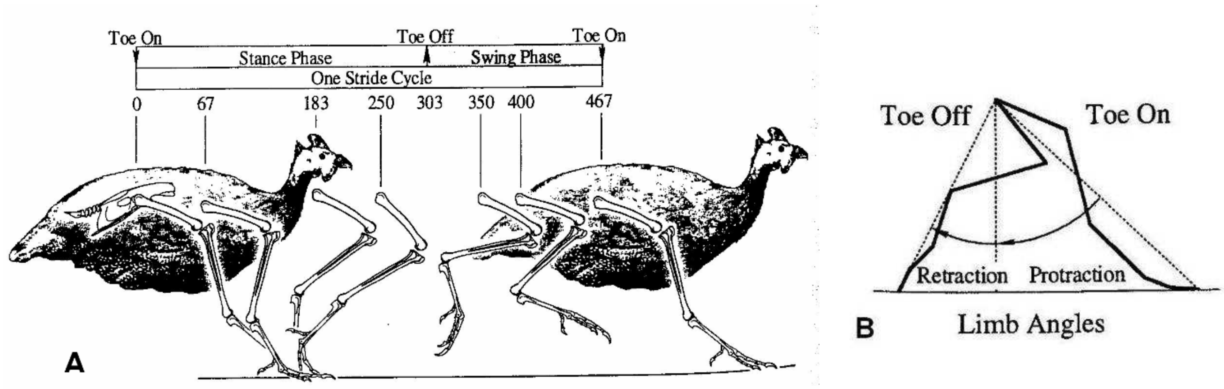


Figure 12: (A) Hind limb movements for a stride in a guineafowl. (B) Limb angles and definion of protraction and retraction angles. Their sum represents the total limb excursion angle. (Adapted from Gatesy 1999b.)

joint (especially the flexion-extension pattern) is generally similar in different avian species and also similar to humans (Rubenson et al. 2007). After foot contact, the knee flexes as the limb compresses drawing the foot backward. At low speed the knee continues to flex throughout ground contact. At higher speeds the knee extends later. Throughout the stance phase, the knee is flexed. In some species, near the end of the stance phase, the knee flexion is briefly interrupted by a small extension (Cracraft 1971; Muir et al. 1996; Gatesy 1999b; Verstappen et al. 2000). At the beginning of the swing phase, the knee flexes more rapidly to bring the foot off the ground. During swing the knee extends, projecting the foot forward for the subsequent step (Gatesy 1999b; Reilly 2000; Verstappen et al. 2000). Finally, in ground-feeders, prior to landing, the knee is extended, only slightly more than required for the completion of the walking cycle, while upon landing it is flexed (Cracraft 1971). Earls (2000) studied the take-off kinematics in two avian species and found that the intertarsal angle (defined by tibiotarsus and distal tarsometatarsus) in the starling ranged 120-155^{o}, but in the quail 45-163^{o}.

In ratites, which are the ultimate gaiters, the yield phase is weak and is achieved with the hip and knee flexed in cassowaries and only the knee in rheas and kiwi (Abourachid and Renous 2000). In the running ostrich, the knee contributes both to toe lifting and return to the ground (Rubenson et al. 2007). The knee presents a mean external rotation angle of 37^{o} with its minimum value (31^{o}) occurring just prior to mid-stance and its maximum (42^{o}) prior to toe-strike (Rubenson et al. 2007). At this point it would be important to stress that during the early and middle part swing phase, external tibiotarsal rotation and valgus motion of the knee joint aids in abducting the lower limb segments from the centreline, improving the clearance between stance and swing phase. Subsequently, the large varus motion and internal rotation during the end of the swing phase contributes to returning the phalanges underneath the body (Rubenson et al. 2007). These coupled motions have been detected also in pigeons (Cracraft 1971; Fuss 1996). To accurately evaluate them, a 3-D analysis should be applied otherwise the two dimensional examination could lead to considerable misinterpretation with clinical importance (e.g. adduction interpretated as flexion) (Rubenson et al. 2007)

Moreover, the knee angle is also influenced by speed and its possible changes. In less pedal species compared to the ratites, but still major ground dwellers such as guinea fowl, the arc of knee flexion during the stance (propulsive) phase is large at all speeds, averaging between 45-65^{o} (Gatesy 1999b). In the higher speed range, movement is initiated by knee flexion and then augmented by hip and knee extension later in the stance phase, but the knee remains the primary joint at which the body rotates over the foot (Gatesy 1999b; Reilly 2000). Additionally, the femur is abducted 10-15^{o} throughout the stride (Gatesy 1999b). According to Reilly (2000), the maximum knee angle in the quail at the beginning of the swing phase increased approximately 20^{o} over the speed range, while the overall knee excursion increased in a similar amount solely by extending the knee farther during the swing phase. This increase of excursion during stance phase as speed increases, keeping the ankle (tibio-metatarsal joint) static, is a unique characteristic of quail locomotion.

3.3 Luxation: aetiology and frequency

3.3.1 Luxations in avian species

Luxations occur infrequently, compared to other orthopedical conditions, in most of the avian species (Martin and Ritchie 1994). According to Schuster (1996) one in ten birds, presented with wing or shoulder girdle fracture, was also accompanied by a respective luxation. The most commonly affected avian taxonomic groups are psittacines, small cage birds, raptors, pigeons and waterfowl (see also *Table 2*). These are presented to the avian practioner as companion birds, wildlife casualties, falconry birds or residents of a zoological collection. Additionally, luxations are a frequent problem in commercial broiler farms due to excessive weight gain over a short period. Subsequently, it is easily understandable that the spectrum of species and husbandry purposes represent a plethora of variations in frequency, appearance, causality and fixation techniques for luxation, in birds.

Table 2: Avian orders and luxation incidences as represented in the published literature (1979- 2010).

Avian order	Approximate number of described incidences *
Pelecaniformes	2
Anseriformes	7
Falconiformes	16
Galliformes	1 (except commercial poultry)
Gruiformes	2
Charadriformes	2
Columbiformes	30
Psittaciformes	13
Strigiformes	2
Piciformes	2
Passeriformes	1
Struthioniformes	1
* Some publications do not refer the exact number of cases	

In the following chapter, an overview will be presented of the most important described luxation types, naming the species, the causes, and the clinical signs. In Table 3 a cumulative number of the published cases for each luxation are presented. It is here important to note that luxations are often underdocumented and therefore the data should be critically interpretated. The fixation methods and the prognosis will be described in a subsequent, separate chapter. Short reference will be made to angular limb deformities, which are often present in growing long-legged avian species.

Table 3: Numeral overview of published luxation data (1979- 2010)

Luxation localization	Approximate number of published incidences *
Palatine bone	1
Coracoid bone	1
Scapulohumeral joint	41
Elbow joint	26
Carpometacarpal joint	5
Metacarpophalangeal	2
Coxofemoral	10
Stifle joint	23
Intertarsal	4
Vertebral (notarium-synsacrum)	2
* Some publications do not refer the exact number of cases	

3.3.1.1 Coracoid luxation

This luxation is usually associated with chest injuries, after colliding with a solid object (Holz 2003; Guzman Migallon-Sanchez et al. 2007), and is repaired surgically, only if the coracoid bone is dislocated from the sternum. Upon physical examination birds are presented either with a wing droop or normal wing holding posture, are unable to fly or fly short distances, while crepitus may also be detected. To verify the luxation radiographs should be taken (Olsen et al. 2000; Holz 2003; Guzman Migallon-Sanchez et al. 2007). A case of caudoventral luxation of the left coracoid, affecting both its distal and proximal articulation, was recently described in a bald eagle (*Haliaeetus leucocephalus*) (Guzman Migallon-Sanchez et al. 2007).

3.3.1.2 Shoulder luxation

The scapulohumeral joint is generally described as a stable joint due to the local supporting musculature and coracohumeral ligament (Coles 1997). Luxations of the shoulder have been reported for snow geese (*Anser caerulescens*) and Ross's geese (*Chen rossii*) (Wobeser et al. 1981), in ostrich (*Struthio camelus*) (Zonghuan 1997), in raptors (Martin and Ritchie 1994; Souza et al. 2004), in one crow (*Corvus corone*), pigeons (*Columba livia domestica*) and gulls (Coles 1997). Finally, in a study focused in avian fractures, 15 shoulder luxations out of 49 fractured shoulder girdle cases, were identified (Schuster 1996). The main cause is rupture of the tendon of the supra-coracoideus muscle, leading to upward subluxation of the humeral head. This is usually accompanied by an avulsion fracture of the ventral tubercle of the proximal humerus (Martin and Ritchie 1994). Reluxation after treatment is not uncommon (Bennett 1997).

3.3.1.3 Elbow luxation

Elbow luxations are common in wild birds, but infrequent to rare in companion birds (Bennett 1997; Hatt 1999). In various raptor species it represented a percentage of 2% and 12% of the caseload in two raptor centers (Martin et al. 1993b; Ackermann and Redig 1997). Moreover, Souza et al (2004) have reported seven cases in raptors, from which only three returned to the wild. A permanent left elbow luxation has been also recorded in a Mauritius pink pigeon (*Columba mayeri*) (Flach and Cooper 1991). Another study (Schuster 1996) reported 18 elbow luxations (with mostly radius involved) in 239 wing fracture cases. These luxations usually result after a severe blunt trauma strong enough to disrupt the ligamentous support. Ackermann et al (1997) described the avian elbow joint as a swallow joint lacking trochlear notch, annular, collateral and olecranon ligaments. The supporting structures of the joint is a weak capsular membrane (common to humerus, radius and ulna) two transverse radioulnar ligaments and the extensor and flexor muscles (Ackermann and Redig 1997). Additionally, the elbow contains a cartilaginous meniscus (Roush 1980). Because of the above-mentioned anatomy, the most common type of luxation is the caudodorsal (75%) (Ackermann and Redig 1997) followed by the caudal (37%) (Martin et al. 1993b). Ventral luxation occurs when a radial fracture is present (Bennett 1998). The patient holds the affected wing extended (drooped) and rotated up to 90^o, while crepitus, swelling and pain are common findings in palpation. Special attention should be directed at open wounds and soft tissue injuries as they could affect the release prognosis (Martin et al. 1993b).

3.3.1.4 Carpo-metacarpal joint luxation

Carpal luxations are generally ventral and occur mostly in the effort of the bird to release the entangled wing from the aviary cerclage. Clinically, the bird holds the wing with carpus extended and laterally rotated (Bennett 1997; Hatt 1999). Furthermore Roush (1980) adds, that when one wingtip seems “floppy”, a slight luxation between metacarpal and phalangeal bones may be suspected. Doty (1979) reported a compound luxation to the carpus in a radio-fitted Canvasback duck (*Aythya valisineria*), which healed without treatment within 17-19 days. The duck was able to burst flying and long-distant flying (2.5-4 km). An interesting case of carpal joint luxation was reported by Rajchard and Rachac (2003). Free-living, juvenile black-headed gulls (*Larus ridibundus*) were presented with rotation of the metacarpal bones, but without any fracture suspicion. The authors believe that this post-traumatic state may have resulted when the developing birds stuck in the viscous mud around the nest colony. Schuster (1996) has also reported few cases in wild and pet birds.

A condition, which affects the carpo-metacarpal region, is the “angel or slipped wing”. It is commonly described in waterfowl bred in captivity, although appearing in semi-wild waterfowl too (Kreeger and Walser 1984; Olsen 1994), while it has been reported in psittacines, bustard chicks and a Northern goshawk *(Accipiter gentilis)* (Zsivanovits et al. 2006). This condition typically occurs in growing animals, while the primaries are in full developement. According to Kreeger et al (1984) the left wing is mainly affected and the males are more susceptible. Nutrition (excessive energy and or deficiency in Vitamine E and D), limited excersice, genetic factors and management practises have been implicated (Olsen 1994).

3.3.1.5 Coxo-femoral joint luxation

Avian patients with coxofemoral luxation are occasionally presented in the avian practice (Roush 1980). Currently it has been reported in small birds (Martin and Ritchie 1994), in a hyacinth macaw (*Anodorhynchus hyaccinthinus*), an African grey parrot (*Psittacus erithacus*) a Moluccan cockatoo (*Cacatua moluccencis*) (MacCoy 1989), a yellow collared macaw (*Ara auricolis*) (Martin et al. 1994), a Toco toucan (*Ramphastos toco toco*) (Campbell 1987) and two cormorants (*Phalacrocorax carbo*) (Risi et al 2005). Altman (1982) suggests that it is more common in pet birds, weighting up to 1 kg. The prevalent cause is entanglement of the bird's limb in a curtain or the cage and subsequent struggle to free it or improper handling (Martin et al. 1994; Hatt 1999). The leg is fixed in extension and instability and crepitus is detected in palpation (Hatt 1999). According to McCoy (1989) the coxofemoral joint is diarthroidal with a round ligament and collateral ligaments. In some species a prominent antitrochanter exists as an extension of the pelvis, dorsal of the coxofemoral joint. Ventral collateral and round ligaments play major roles for the proper position of the femoral head in the acetabulum, especially in non-cursorial species such as psittacines, hawks, falcons, owls and pigeons (MacCoy 1989). In contrast, cursorial species (e.g. ratites) have a ball-socket type joint (Martin and Ritchie 1994). Traumatic rupture of the femoral capital ligaments promotes commonly a dorsal or craniodorsal avulsion of the femoral head (Altman 1982), although Martin et al (1994) have described a cranioventral case.

3.3.1.6 Intertarsal joint luxation

Intertarsal luxation is occasionally observed and, in adult birds, is usually due to severe trauma. Dislocation is frequently accompanied by damaged tendons, ligaments, and integument. Additionally, limb deformities due to nutrinional deficits, could involve non-reducible luxation of the joint with lateral displacement of the gastrocnemius tendons (Ferraz et al 2010). Unfortunately, there is only minor possibility to repair the joint, and amputation is not an option since it mostly results in pododermatitis of the contra lateral foot. A successful treatment of intertarsal joint luxation in a Denizli rooster (*Gallus domesticus*) was recently achieved by Demirkan and Kilic (2003). Recently three more cases of non-reducible luxation of the tibiotarsal-tarsometatarsal joint were reported in a six-week old *Cacatua sp* and in two sibling three-month old goslings (*Anser sp*), that were corrected with HESF (Ferraz et al 2010). The tibial cartilage can be damaged on its own as growing birds can easily dislocate many of the structures within or attached to the tibial cartilage. The most frequent dislocations involve the tendon of *M. flexor hallucis longus*. The tendon bursts out of position and lies to the lateral aspect of the tibial cartilage as a consequence of trauma. The bird is unable to use the affected leg, there is an obvious thickening of the joint and - if recently displaced-the tendon can be easily palpated. The foot is rotated away from the body (Harcourt-Brown 2002), with persistent ligamentous laxicity (Roush 1980).

3.3.1.7 Metatarsal joint luxation

The metatarsophalangeal joints are not very susceptible to luxations (Roush 1980) and may be dislocated without ligamentous damage (Harcourt-Brown 2002).

3.3.1.8 Various reported luxations

Other less common luxations include ***(sub)luxation between notarium and synsacrum on the sixth thoracic vertebra*** in falcons (Harcourt-Brown 2000; Naldo and Samour 2004), ***metacarpophalangeal luxations*** in a juvenile prairie falcon (*Falco mexicanus*) and a great horned owl (*Bubo virginianus*) (van Wettere and Redig 2004) and **a *palatine bone luxation*** in two blue and gold macaw (*Ara ararauna*) (Martin and Ritchie 1994; Foerster et al. 2000). In the first occasion, falcons showed poor flight performance, unilateral or bilateral lameness to severe paresis or paralysis. The vertebral-synsacral junction was most easily damaged, after collision with a solid object. Euthanasia was proposed, as conservative therapy is usually unsuccessful. According to the metacarpophalangeal luxations, these are rare, representing 0.13% (2/1579 cases) over a two-year period at the Raptor Center-University of Minnesota. The prairie falcon had a dorsal, partially stable, with fibrous callus metacarpophalangeal luxation of the right wing accompanied by a distal complete articular fracture of the major metacarpus and a distal fracture of the minor metacarpus. The great horned owl was diagnosed with an open, dorsal, unstable, with large fibrous callus luxation of the left wing. Arthrodesis was applied successfully in both cases, permitting full flight capability and return in the wild. Finally, palatine bone luxation has been recorded twice. The affected blue and gold macaws *(Ara ararauna)* showed hyperextended maxillary beak and presented with a history of acute head trauma. This type of luxation requires the simultaneous act of a dorsal force with maxillary hyperextension. The successful technique applied, was the introduction of a transverse intramedullary pin across the infraorbital sinus, which was further bilaterally stabilized around the suborbital arch and jugal bones with absorbable sutures. In one case the patient succumbed due to anesthetic complications, ruling out wrong introduction of the pin. The second macaw returned to normal beak function.

3.3.1.9 Angular limb deformities

Angular limb deformities (*Os tarsometatarsalis*) have been recorded in Psittacines, Falconiformes, Strigiformes, ratites (Haeffner 1989; Gilsleider 1994; Crabill and Honnas 1996; Gnad et al. 1996; Bennett 1997), king penguin (*Aptenodytes patagonicus)* (Henderson et al. 2002), cranes (Carpenter 2003), flamingoes (*Phoenicopterus ruber*) (Zollinger et al. 2005) and other long-legged birds (Kirkwood 2000). A causal relationship has been established between nutrition, genetics, trauma from the parents, malposition within the egg, inappropriate exercise, nest substrate and other factors (Clipsham 1991a). The syndrome involves a thickening and a lateral deviation of the tibiotarsometatarsal joint in chicks less than 3 months old. The deviation can cause a 180^{o} degree rotation from the dorsoplantar axis of the normal leg in only few days (Samson 1997). Usually only one leg is affected and not all chicks from a clutch show the problem (Coles 1997). Various methods have been described for the correction of this condition like Dome osteotomy, external skeletal fixation, transphyseal bridging technique, tarsometatarsal Wedge osteotomy and others. Conservative management (swimming, diet change, hobbling, slowing of weight gain, genetic selection, control of trauma by parents etc.) is needed along with surgical treatment.

3.3.2 Femorotibial joint luxation in avian species

Luxations of the femorotibial joint have been recorded in a variety of species, including, a Monk parakeet (*Myiopsitta monachus*), a green-winged macaw (*Ara chloroptera*), in peach-faced lovebirds (*Agapornis roseicollis*), in cockatiels (*Nymphicus hollandicus*), in grey parrots *(Psittacus erithacus*), in blue and gold macaws, in scarlet macaws (*Ara macao*) (Bowles and Zantop 2002), in a military macaw *(Ara militaris*) (Donato 2000), in a Moluccan cockatoo (*Cacatua moluccencis*) and a barn owl (*Tyto alba*) (Rosenthal et al. 1994), in a blue-fronted Amazon (*Amazona aestiva*) (Alievi et al. 2001), in a Solomon Island Eclectus Parrot (*Eclectus rotatus solomonensis*) (Harris et al. 2007) in a white-fronted goose (*Anser albifrons*) (Fukui 2005), in a Major Mitchell cockatoo (*Cacatua leadbeateri*) (Holz 1992), in a common buzzard (*Buteo buteo*) (David 1976), in a peregrine falcon (*Falco peregrinus*) (Naldo and Samour 2002) and in a trumpeter hornbill (*Bycanistes bycinator*) (Chinnadurai et al 2009). Additionally, a medial patellar luxation was described by Jaffe et al (Jaffe et al. 2000) in a blue and gold macaw (*Ara ararauna*). Sporadic femorotibial joint luxations in various species of wild and pet birds during a four year examination period (1990-94) have been also reported (Schuster 1996).

Excessive forces applied to the stifle region are more likely to produce fractures of the femur or tibia than cause a luxation (Roush 1980). Generally luxation could result from developmental abnormality (Clipsham 1991a; Bennett 1998), spontaneous orthopedic disease (Harcourt-Brown 2000), and traumatic episodes (Bowles and Zantop 2002; Fukui 2005). In more detail, the following causes of stifle luxation in falcons have been described: the landing process, especially in untamed birds tethered with an inadequate leash on a perch; gunshot injury; accidents (collision) in the moulting room; and finally handling by novice keepers (Naldo and Samour 2002). The luxation occurs craniolaterally, craniomedially, caudolaterally and caudomedially with concomitant damage to the collateral ligaments and cranial/caudal cruciate ligament (Duff 1985; Clipsham 1991a; Fukui 2005), while meniscal damage is rarely diagnosed (Harcourt-Brown 2000). Nevertheless the tibiotarsus shows no specific propensity to luxate in a particular direction (Bowles and Zantop 2002). The muscles that flex and extend the joint may contract significally after luxation making re-positioning of the initial trauma and luxation difficult. Muscle and nerve damage may cause paresis or paralysis of the pelvic limb, resulting in ambulatory difficulty or inability to grip or perch (Flammer and Clubb 1994; Martin and Ritchie 1994). Clinical findings such as hyperextension of the joint, a positive withdrawal sign and also medial or lateral instability on examination, the absence of palpable fracture, lack of crepitus, non-weight-bearing lameness, firm swelling (Naldo and Samour 2002) and the ability to partially reduce the tibiotarsus into its normal anatomic position suggest a luxation more than a fracture (Villaverde et al. 2005). A definite diagnosis can only be made radiologically (Bowles and Zantop 2002).

3.4 Luxation treatment methods

Many techniques have been developed to facilitate luxation management and treatent in birds.

Previously, it was thought that a luxation of an avian joint was unlikely to be successfully treated with full or at least functional recovery. Today a luxation is not *per se* considered “a lost case”. On the contrary, attempting to salvage a joint it may prove unexpectedly rewarding if early diagnosis and proper management technique selection is applied. According to Bennett (1997) periarticular fibrosis may develop within three days, inhibiting the full recovery of the luxation and predisposing to joint ankylosis. Additionally a proper technique should be correctly applied to avoid permanent ligamentous laxicity caused by false anatomical reposition and even regular reluxation. The stabilisation before joint stiffness and the necessity of physical therapy appear to be of equal importance (Roush 1980). Evidently, a variation in prognosis also exists, depending on the luxation site, the intervention time and the accompanying findings (open luxation, soft-tissue damage, ruptured tendons, ligaments, periarticular fractures, muscle contraction etc). In the later cases the prognosis is guarded to poor.

The subsequent chapter summarises the various techniques used so far to stabilize an avian luxation with main emphasis on stifle repair, where all past techniques will be in detail described.

3.4.1 External coaptation and cage rest

External coaptation is one of the simplest, fastest, and most cost effective methods for fracture and luxation fixation. Nevertheless, in most cases it is unrewarding, has a high percentage of fracture disease (Anderson 1991; Bennett and Kuzma 1992) and the return to function is typically prolonged, due to incomplete immobilization. Furthermore, it may predispose to stress, death and pododermatitis (Bennett 1997). Therefore, it should only be considered as an emergency method, until surgery can be performed (Martin and Ritchie 1994; Harcourt-Brown 2002). Only some luxations can fully recover with cage rest and a simple bandage only and regain their full range of motion. Many authors propose that coaptation should only be considered when the full return to function is not required, the anesthetic and surgical risks are too great, the patient is too small for internal fixation, and when the luxation is accompanied by pathologic fractures as result of metabolic bone disease (Martin and Ritchie 1994; Bennett 1997; Helmer 2006)

3.4.1.1 Bandages, splints and casts

The most commonly used bandages and splints to stabilize fractures and partly luxations, in avian medicine, are the “figure of eight” bandage, the ball bandage, the Robert-Jones bandage, the Altman splint, the Schroeder–Thomas splint, the Mason-Meta Splints, the Spica splints and the Acrylic toe splint. Wood applicator sticks, tongue depressors, aluminium rods, Hexcelite (Hexcel Medical, Dublin,CA), Orthoplast (Johnson & Johnson Products, Inc, New Brunswick, NJ) and Veterinary Thermoplastic (VTP; Imex Veterinary Inc, Longview,TX) (Hess 1994; Bennett 1997) have been used as splinting material. The splints are mainly used as first-aid or supportive measure after surgical correction. For their application anesthesia is usually required (Rupley 1997) to avoid increase stress, even though the intervention may appear as a simple, non-invasive action. A bandage is usually applied three to five weeks, with at most weekly changes (Rupley 1997). The detailed application procedure and the indications of each splint type have been extensively reviewed in the avian literature.

In general, the splints should be made from the lightest possible material, offering also stability with minimal amount of padding, needed to compensate for soft-tissue swelling (Martin and Ritchie 1994). The bandages should consist of multiple layers. The primary layer is made out thinly, while in the second thicker layer of padding, a form of splint is often incorporated to offer extra stability. In tape splints (e.g Altman splint), two layers should be applied for smaller birds and three to five for larger birds (Hess 1994). The bandage should always be clean and dry, and the bandaged extremity should be regularly checked for swelling due to constriction by the bandage. In psittacines, gauze must be avoided, as they can pick up individual fibres (Bennett 1997), while red bandages can draw the attention in raptorial species. In particular, the modified Schroeder-Thomas splint has been reported to be uncomfortable to the birds and to encourage adhesions and loss of limb function (Harcourt-Brown 2002).

Regarding the use of splints and bandages in luxation reduction only limited data is available. The ***phalangeal joint dislocations*** were easily corrected, without even the need of external support, which could additionally cause loss of function. Damaged collateral ligaments were repaired with 3-0, 4-0 polygalactin sutures (Harcourt-Brown

1996; Helmer 2006). The “figure of eight wrap” has been successfully applied to reduce ***elbow luxations*** in only two cases of diurnal raptor, but with no post-release follow up; the animals were assumed to have little ligamentous damage and minor instability (Martin et al. 1993b). According to Bennett (1997), ***carpal luxations*** can also be conservatively managed with the “figure of eight bandage” for 7 to 12 days, but if laxicity is present, an open reduction with ESF should be preferred. Additionally, this bandage could act as a supportive measure after elbow open reduction techniques (Ackermann and Redig 1997). In contrast, the use of a “figure of eight bandage” is indicated for ***shoulder luxations*** wrapped around the body for 10-15 days (Martin and Ritchie 1994; Bennett 1997; Olsen et al. 2000) and in ***proximal coracoid luxation*** after open relocation to the sternum (Olsen et al. 2000). Spica splints, slings and casts have been recommended for closed management of ***coxofemoral luxations*** (Roush 1980; Altman 1982; MacCoy 1989; Martin et al. 1994) and for support after femoral head osteotomy (Martin and Ritchie 1994; Bennett 1997). Recently, Villaverde et al (2005) have experimented to fixate a ***stifle luxation*** using a splint applied from the femur to the metatarsal bones, including digits I and III and wrapped with elastic tape (see also Fig. 13). The pigeons could bear weight on the affected limb two to three days after splinting. According to this survey the main disadvantage of external coaptation in stifle luxation is the poor anatomic adjustment to maintain the proper stabilization.

3.4.2 Internal fixation

The term “internal fixation” refers to the use of various materials applied alone or in combination to the medullar cavity and the cortices of the bones to permanently immobilize a fracture. Generally, all implanted materials should be removed when radiographic union has taken place, except for cerclage wire (Harcourt-Brown 2002). The following methods have been proposed for fracture fixation: intramedullary pinning (alone or in combination with external coaptation, external fixation, cortical screw and cerclage wire), bone plating, orthopedic wires, absorbable IM polydioxanone pins, polypropylene rods, shuttle pins, intramedullary polymethylmethacrylate (PMM) and intramedullary PMM with a pin or rod (Bennett 1998). Internal fixation requires the use of anesthesia and may be prolonged in difficult cases. Many authors have reviewed the advantage and disadvantages of each method in fracture repair (Roush 1980; Bennett and Kuzma 1992; Hess 1994;

Martin and Ritchie 1994; Bennett 1997; Harcourt-Brown 2002), but only few commented on their use in luxation management (Roush 1980; Martin and Ritchie 1994; Bennett 1997). These comments are presented below.

3.4.2.1 Intramedullary (IM) pinning

The use of intramedullary pins has been recently described for ***stifle luxation*** in birds, although earlier Roush (1980) had proposed the transfixation of ***shoulder*** and ***coxofemoral luxations*** with a smooth unthreaded Steinmann pin. The pin is inserted through the trochanter into the head of femur and across the acetabulum. A pre-measured pin and careful insertion are needed to avoid kidney injury. First Zantop (2000) and later Bowles and Zantop (2002) reduced a craniolateral and a medial luxation in two monk parakeets (*Myiopsitta monachus*) and an umbrella cockatoo *(Cacatua alba)* inserting two normograde IM pins. A 0.045-inch diameter Kirschner wire was normograted into the tibiotarsal bone medially to the patellar ligament, while a similar second wire entered the femoral cavity from the greater trochanter. The exposed portion of each pin was cut 2 cm from the joint, in a way that the end of each pin was bent 90^{o} cranial to its insertion. Subsequently, acrylic, formed in a ball, was placed over the pins to provide stability. Villaverde et al (2005) followed this technique in experimental ***stifle luxation*** in pigeons to compare it with other stifle fixation techniques (see also Fig. 13). Recently, a craniolateral luxation of the femur was fixed similarly, with the modification of conjoined edges of the intramedullary pins, bended in 90^{o} each other (Harris et al. 2007). Finally, two cases of ***palatine bone luxation*** have been treated with a transverse intramedullary pin crossing the infraorbital sinus to displace the palatine bones ventrally. Then the IM pin was removed and the reduced palatines were bilaterally stabilized around the suborbital arch and jugal bones with 3-0 polydioxanone absorbable sutures (Foerster et al. 2000).

3.4.2.2 Extra-capsular stabilization techniques

Cortical screws and tension bands have been also frequently used to correct a luxated joint in the avian patient. Jaffe et al (2000) fixed a 1.5 mm and 16 mm long cortical bone screw to the lateral femoral condyle of a macaw, to reduce a grade IV ***medial patellar luxation***. A single strand of 0-nylon suture was threaded to the proximal cnemial crest and anchored to the screw head, with the stifle aligned in a normal position. Villaverde et al (2005) used two variations of this technique to reduce an experimental mediolateral **stifle luxation** pigeons. A group of pigeons were treated with a cortical screw and a 3-0 nylon band through the fibular crest, while a second group was treated by an extra nylon suture to the space between fibula and tibiotarsus, ventral to the fibular head creating a double tension band anchored to the cortical screw (see also Fig. 13). Another stifle reduction method using solely a 20 gauge cerclage wire was investigated by Holz (1992). The wire was passed lateromedially, through pre-drilled holes in the distal femur and the proximal tibiotarsus, and knotted laterally to act as collateral band, preventing the mediolateral movement of the femorotibial joint. To further tighten the fixation, Holz sutured the muscles with 4-0 Dexon. Additionally, a Thomas splint was applied for 15 days. Finally, the tendinous origin of the lateral head of the gastrocnemius muscle was tightened to the tibial tuberosity using a non-absorbable suture with good results in a white fronted goose (*Anser albifrons*) (Fukui 2005). Two stifle luxations one in an trumpeter hornbill (*Bycanistes bucinator*) and one in an African grey parrot (*Psittacus erithacus*) were reduced with a nylon suture drilled through the tibial tuberosity and anchored around femoral origin the lateral collateral ligament or craniocaudally through a hole in the lateral femoral condyle (Chinnadurai et al 2009). ***Intertarsal joint luxations*** were also successfully reduced using cerclage wire, Teflon suture or polyester suture in a “figure of eight” pattern passed through drilled holes in distal tibiotarsus and proximal tarsometatarsus (Roush 1980; Harcourt-Brown 1996; Demirkan and Kilic 2003).

3.4.2.3 Bone plate

The only case of luxation repair with bone platting has been reported by Guzman Migallon-Sanchez et al (2007). A caudoventral ***coracoid luxation***, affecting both clavicular and sternal articulations, was successfully repaired using a combination of 4-hole, 1.5 mm T-plate, a six hole, 2.0-mm dynamic compression plate and two cerclage wires. The distal coracoid-sternum luxation was reduced with the two plates placed side by side, whilst the claviculo-coracoid luxation was reduced with two cerclage wires in a simple interrupted pattern. Forty–five days after surgery the bald eagle (*Haliaeetus leucocephalus*) was capable of flight.

3.4.3 External skeletal fixation

The external skeletal fixation is a well established method for fracture management in small animal and avian surgery (Bennett and Kuzma 1992; Bennett 1997; Kraus et al. 2003). The method is characterised by two fundamental components; the fixation pins and the connecting column (fixation frame), regardless of the applied device or system (Kraus et al. 2003). The pins can be classified as half or full. The former penetrate the skin, muscles and bone cortices in the one side of the bone, whereas the latter continue to emerge from the other side of the limb. The half pins are threaded at the end in contrast to the full pins, which are centre-threaded. The advent of superior fixation pins has lead to the minimising of pin loosening incidents and to the application of external fixation in the most challenging fractures. The column is exclusively located outside of the skin and connects with the fixation pins providing stability. Different systems have been developed in veterinary medicine, such as the Kirschner-Ehmer, the Securos, the IMEX-SK and the acrylic pin external fixator (APEF). Two or more bars can be interconnected with linkage devices (articulations) to increase the overall strength of the system.

Currently, three basic types of fixators are available; unilateral (Type I), bilateral (Type II) or multiplanar (Type III) (*Table 4*)

Table 4: Nomenlature of external skeletal fixation categories

Type Ia	At least two half-pins per proximal and distal fracture segment connected with one unilateral column
Type Ib	Two Type I frames situated usually in 90^{o} angle, interconnected or not with linkage devices.
Type I Tie-in	A unilateral system connected with an intramedullary pin
Type II	At least one full pin per proximal and distal segment (with additional half-pins), connected with two columns that span the fracture
Type III	A unilateral or Type Ia fixator added to a Type II frame, usually with orthogonal orientation, creating a three dimensional frame configuration

A number of combinations could be achieved among Type I, Type II and internal fixation methods.

Recently, the use of *hinged linear external fixators* (HLESF) in small animal surgery has been favoured for the management of shearing injuries, traumatic luxations with ligament rupture, juxtaarticular fractures and tendon or muscle repair (Marcellin-Little 2004b; Marcellin-Little 2004a). ***Transarticular ESF*** is characterized as the temporary placement of a frame across a joint for stabilization or immobilization. For the stifle, unilateral linear ESF frames have been classically recommended, although the use of a Type II transarticular Kirschner-Ehmer with curved bars and contoured connecting rods as well as a Type II biphasic splint have also been described (Toombs 1992).

In avian medicine, various ESF models have been proposed and modified to comfort the special needs of the avian patient, such as bipedalism and flight, ethology, small size, thin bone cortices, bone pneumatisation, poor soft tissue protection, and vascularisation of the extremities. Grimm (1993) experimented with a modified external fixator, using the 2 mm Schanz screws. The connecting bar was made of carbon fibre-reinforced synthetics and aluminium joints to reduce the weight of the fixator. The fixator proved useful only in birds weighing more than 600 gr. Earlier, various authors had already used the Kirschner-Ehmer splint in original or modified version (Bush 1977; Satterfield and O'Rourke 1981; Redig 1986). Limitations to its use were the weight and the cost (Bennett and Kuzma 1992). The Brinker-modified full pin splint had fewer elements and an epoxy connecting bar (MacCoy 1986). The Doyle technique came to compensate for problems of the intramedullary pinning such as periarticular tissue damage, trabecular damage, excessive weight of ESF, and joint compromise. Intramedullary pin and K-wire or hypodermic needles are inserted in the fractures segments, and the ends are bent and kept in firm compression with a ruber band (Martin and Ritchie 1994). Additionally, biphasic fixators and light-weight connecting bar fixators have been described (Bennett and Kuzma 1992). For the later Manuflex (Trade-Coop, Budapest, Hungary), a soft metal with numerous holes was used (Bennett and Kuzma 1992). In 1996 a Type II ESF was applied to twelve birds (game, psittacine and pigeons) with tibiotarsal fractures or angular limb deformity (Meij et al. 1996). The fixator served in intertarsal joint arthrodesis and fracture stabilization, while radiographical healing occurred 10 to 13 weeks later. The authors attributed complications in two cases (malunion and delayed union) due to technical errors. The successful application of a tie-in fixator (TIF) was first reported by Redig (2000) for long bone fracture management. The method was applied in wild raptors and, compared with the standard methods used until the mid 90's, showed a significant raise of the percentage of full return to function from 40% to 65%. The TIF consists of a conventional intramedullary pin, which fills the 50-65% of the marrow cavity, and two or more positive profile-threaded pins linked to the IM pin by a metal or acrylic connecting bar (Redig 2000). Rochat et al (2005) proposed the use of a Type Ia hybrid fixator for a varus malunion in a bald eagle. After an open wedge osteotomy, they fitted a hybrid ESF (HESF) consisting of a 6.3 mm titanium hybrid rod, a 50 mm aluminium ring, four fixation half-pins, clamps and fixation wires. Bone healing succeeded 63 days later and the HESF was removed. The bird was successfully reintroduced to the wild with no deficits, after one month of physical therapy.

Some of the above techniques were also tested for the treatment limb luxations, with variable outcomes, and will be viewed in detail later.

3.4.3.1 Biphasic fixators in a transarticular Type I scheme

Biphasic fixators consist of Kirschner wires of various sizes, Ellis pins or Steinmann pins, and a connecting bar made by acrylic polymer. Polymethyl metacrylate, dental acrylics, Hexcelite or epoxy glue inserted in a Penrose drain can be used (Bennett and Kuzma 1992). Such a fixator formed by Kirschner wires and epoxy as connecting bar was proposed for a ***stifle luxation*** in psittacines by Clipsham (1991b). Preferably, three pins should be fixed in each bone, with the femoral pins placed first. Post-operatively bruising may appear for three to five days, as well as after pin removal. According to the author, the healing time ranged within 21 days in smaller species to 40 days in larger ones, with mild tolerance of the device. Rosenthal et al (1994) used fifteen 0.8 mm Kirschner wires, linked to a PMA bar, to stabilize in functional angle a stifle luxation in a Moluccan cockatoo (*Cacatua molucccensis*) and a Barn Owl (*Tyto alba*). This Type I ESF proved satisfying since the birds could bear weight one hour post-operatively and complete healing was achieved after five weeks. The affected stifle presented a 50% decrease of normal range of motion. Femorotibial joint arthodesis with a Type I ESF has been similarly achieved (Donato 2000; Villaverde et al. 2005), while a ***combination of Type I (femur) and Type II (tibiotarsus)*** was used to reduce a craniolateral luxation of femur in an Amazon parrot *(Amazona aestiva*). After 60 days, a complete osseous union could be detected (Alievi et al. 2001) (see also Fig. 13)*.* Additionally, arthrodesis of a ***metacarpophalangeal joint luxation*** in two raptors, with full functional flight restoration and return to the wild, was recently achieved by van Wettere and Redig (2004) using a transarticular ESF (Type I) consisting of four positive-profile threaded stainless steel pins. The birds were releasable in 17 and 19 weeks post-surgically with no deficits in all types of flight (landing, turning, descending, stooping and catching live prey). Finally, an ***elbow luxation*** repair in two raptors with Type I ESF resulted in 95% function restoration (Martin et al. 1993b). The technique, with the two acrylic connecting bars parallel to each other, was modified by Forbes in 1995 (Forbes, pers. comm. on p. 184 in Coles 1997) in a way that the K-wires are already fixed to the bars before inserting the bone. Moreover a slight flexure and simultaneous rotation of ulna and radius may help in repositioning.

3.4.3.2 Triangular transarticular type I fixator

This type of fixator was proposed to repair closed ***elbow luxations*** with minimal soft-tissue injuries in five raptors (Ackermann and Redig 1997). The fixator was produced by inserting half pins into the dorsal humerus and two into the dorsal ulna. Two plastic tubes were placed to connect the humeral and ulnar pins separately. To provide additional stability, two 0.062 mm stainless steel pins, one at the apex and the other at the base, were bent to fit in the tubing, connecting the pins with PMM (Technovit Laboratories, Inc, Loveland, CO, USA) in a triangular mode. Three of the five birds were released with an elbow range of motion within normal limits (two cases) or small deficit (25% of normal). Although the rehabilitation phase lasted up to six months, the post-release survival of the birds is not known due to lack of long-term monitoring. A similar technique was proposed for the treatment of ***stifle luxation*** by Olsen et al (2000) formed by four positive profile pins connected with one acrylic-filled latex. A second fixator bar would connect the proximal femoral pin with the distal tibiotarsal pin forming a triangular (see also Fig. 13).

3.4.3.3 Type II fixator

A Type II fixator was tested to reduce a caudodorsal ***elbow luxation*** in a prairie falcon (*Falco mexicanus*). The two 0.062 inch K-pins were linked to two methyl methacrylate bars. After 43 days post-operatively, the bird was released with a 95 % range of normal motion without showing crepitus or joint swelling (Martin et al. 1993b).

3.4.3.4 Hinged linear external skeletal fixator

Recently, chronic intertarsal joint luxations with subsequent tibiotarsal rotation and tendon displacement have been corrected with a prototype of HLESF as described by Ferraz et al (2010). The prototype fixator was constructed of three hinged titanium bars (with 6 mm diameter and lengths of 3.5, 3.0, 2.5 cm). The joints were allowed a free uniplanar range-of-motion, but could also be fixed with a 3 mm screw. Bars attained many holes of 2 mm diameter to accept the pins. The total weight of the fixator was 9.5 gr and together with the fixation pins approximately reached the 14 gr.

3.4.3.5 Methods of treatment of coxofemoral luxations

Two newer *open* techniques than the transfixation pinning previously proposed by Roush (1980) have been described to reduce ***coxofemoral luxations*** in birds: excision arthroplasty with femoral head/neck osteotomy (Campbell 1987; MacCoy 1989), and femoral head stabilization with two polypropylene sutures (Martin et al. 1994) or modified Meij-Hazenwinkel-Nap technique (Risi et al, 2005).

Femoral head osteotomy has proved to be a viable, pain-free, salvage procedure to return some degree of normal function when a closed reduction is not possible (Martin et al. 1994). The surgical approach may be caudolateral (MacCoy 1989; Martin et al. 1994) or dorsal (Campbell 1987). The femoral head exposure is similar to the one used in mammals; after aseptic preparation, a linear incision from a point dorsal to the antitrochanter to proximally two thirds the distance to the stifle is made. The iliotibialis and iliofibularis muscles are identified and retracted. The femoral neck is transected with a bone cutter and any rough edges are smoothened with a rasp. An iliofibularis muscle stripe is used to form a muscle sling, encircling the femoral shaft and attached to the main muscular belly (MacCoy 1989). After femoral head reduction, two 4-0 polypropylene sutures are passed through the major trochanter and then through the ilium on each side of the acetabulum. The ends are tied together. Subsequently, a Spica-type splint is applied using a 20 gauge wire dorsal to the pelvis along the opposite leg (Martin et al. 1994). According to the author, this technique is safer and provides post-operatively full range of motion of the hip joint. In the modified Meij-Hazenwinkel-Nap technique a non-absorbable woven multifilament suture was passed in a “figure-of-eight” pattern through the acetabulum protuberance and the greater trochanter (Risi et al 2005).

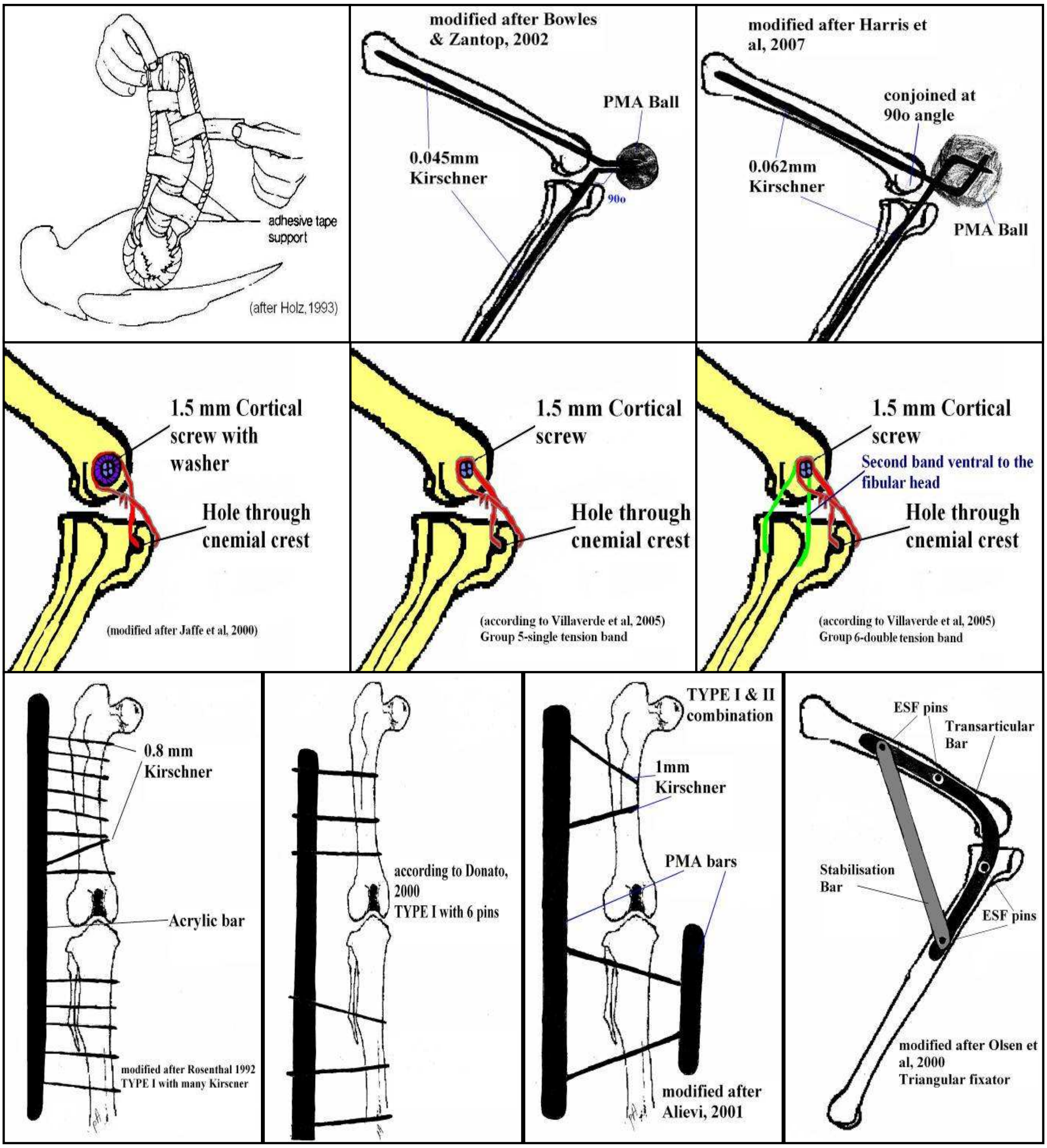


Figure 13: Proposed techniques for stabilizing a femorotibial joint luxation. First row: Splinting (far left). Intramedullary pinning. Second row: Screw and suture combinations. Third row: Type I ESF, Triangular Type I ESF, Type I & II combination.

3.4.4 FESSA external skeletal fixation

The application of the Fixateur Externe du Service de Santé des Armées (FESSA) is an additional method of external fixation, which was primarily developed to accommodate the treatment of fractures in human hands and feet, under combat conditions (Meyrueis et al. 1980). Due to the importance of the system to the present study, a detailed description will be presented in a separate chapter (*see Materials*), while below a review of its use in avian and veterinary medicine will be given.

3.4.4.1 FESSA use in veterinary medicine

The FESSA fixator was intended for and developed under field conditions during the Rwandese war, for human fractures (Labeeu et al. 1996). In veterinary medicine, it has been first used in small mammals, in the end of 1980 by Dr. Chancrin (Girard 2003), although a formal publication appeared only ten years later (Chancrin et al. 1990). In the subsequent years, two veterinary theses (Nardin 1991; Girard 2003) and an advancing number of studies were published, focusing on the use of FESSA in toy and miniature dog breeds, as well as in cats and rabbits (Chancrin 1994; Chancrin 1997; Reichler et al. 1997; Chancrin 2000; Haas et al. 2003; Boulet 2005). In all these studies, the FESSA was favourable, comparable to other ESF systems, in healing time and percentage showing stability, ability for closer placement of Kirschner wires, and easy removal. It was judged as a satisfactory alternative to the use of mini-plates (2.0 mm mini –DCP) for the fixation of distal/ulnar fractures (Haas et al. 2003).

A further interesting application of two 6 mm FESSA tubes combined with a 4 mm threaded rod, with a thread pitch of 0.7 mm (IMEXtm) as a prolonged Type I fixator, was recently described in the successful healing of an ulnar fracture in a cat (Voss and Lieskovsky 2007). Finally, the mechanical properties of the FESSA fixator were challenged when it was applied in two Charolais calves, weighting 75 kg and 83 kg respectively, which presented open, contaminated metatarsal fractures (Chatre 2003). In this case, the fixation system consisted of a “V” mounting with a lateral hemiframe and 6 pins and an anterior hemiframe with four pins and a connecting rod. Both calves healed in a functional outcome, despite the unsatisfactory reduction..

According to the author, although the FESSA is more expensive, it is adequate for heavy and active animals due to its rigidity.

In summary, the FESSA system represents many advantages as an external skeletal fixator, comparable to the traditional ESF apparatus (Orthofix, Kirschner, Meynard, Ilizarov etc) (Meyrueis et al. 1993; Chatre 2003; Haas et al. 2003) in terms of healing outcome, mechanical properties and complications. Moreover, due to its elegance and rigidity, it can be applied in a large number of combinations in veterinary patients weighting from 93 g to 83 kg. And finally, the system can be reused, making it affordable and financially comparable to other systems.

3.4.4.2 FESSA use in avian medicine

The first record for the use of FESSA system in avian patients came quite recently, although the authors had been using it successfully for five consequently years prior to the publication (Hatt and Sandmeier 2003). This first presentation demonstrated the use of FESSA in four fracture cases occurred in two psittacine species (*Amazona aestiva, Psittacus erithacus*) and a tawny owl (*Strix aluco*). All individuals suffered from different types of fractures, namely a closed midshaft humeral fracture, a closed distal oblique tibiotarsal fracture, a closed proximal oblique femoral fracture and a closed comminuted midshaft fracture of ulna and radius. In the above-mentioned cases, the FESSA system was used in various combinations as Type I external fixator combined with an intramedullary pin and a cerclage wire (ulna), as a TIF, and as a Type II fixator. The outcome of all cases was optimal leading to the full restitution of function (Hatt and Sandmeier 2003). In the subsequent years the system was tested in fracture management of free-ranging diurnal and nocturnal raptors (Hatt and Christen 2004). In this study, the fixator was used as a Type I only (six from ten cases), as a TIF (one case), and as a Type I with supporting cerclage wire (two cases) or intramedullary pin (one case). The main complication observed was instability (four cases), while only two cases were treated uneventfully.

Recently, (2007) three more “fracture” studies in avian patients chose the FESSA system as main management tool (Hatt et al. 2007; Hernadez-Divers et al. 2007; Muller and Nafeez 2007). Hernadez-Divers (Hernadez-Divers et al. 2007) applied the 6 mm or 8 mm system in humeral, antebrachial, femoral and tibiotarsal fractures of three common avian families (pigeons, psittascines and raptors), weighing 100 g to 2000 g, with good results. In total (Hatt et al. 2007; Muller and Nafeez 2007), the technique was used as TIF in nine cases, as Type I only in eleven cases, and as Type I plus intramedullary pin in five cases. In the first study (Hatt et al. 2007), three cases presented non-union or osteolysis due to osteomyelitis, while in five experimental cases (pigeons) fissure formation and refracture, around the most distal ulnar pin, occurred. Other complications were instability (in three cases), premature pin loosening (four cases) and possible metabolic disease (one case). Moreover, no difference in the outcome was described between perpendicular or angled placed pins, when a Type II FESSA fixator was applied (Hatt et al. 2007). Finally, (Muller and Nafeez 2007) treated successfully five cases of tibiotarsal fractures in hybrid Gyr-Saker falcons (*Falco rusticolus X Falco cherrug*) using a TIF-Type II fixator. An intramedullary pin was normograted from the lateral condyles of the proximal tibiotarsus and then bended 90^{o} laterally. Two pins (3.2 mm, trocar point, Imex Veterinary Inc. Texas, USA) were perpendicularly placed in the distal and proximal tibiotarsus. The two pins and the IM pin were connected together with the suitable FESSA tubes. In two cases, complications delayed the healing period, in which callus formation was radiographical identified within 7-14 days post-operatively. The birds bore weight on the operated limb 24-48 h after surgery, and could also grasp chopped food with the treated leg at the same frequency as the healthy leg (Muller and Nafeez 2007).

In summary, all authors emphasize the advantages of the FESSA fixator in multiple fracture type repairs, for birds weighting from 93 g to 2000 g. It allows pin repositioning or removal-changing the dynamic stresses of the fracture-, and poses no source of danger, irritation or discomfort to the patient, due to its elegance and small weight. Additionally, the quick use of the operated limb promotes the healing and protects the contralateral limb from developing pododermatitis.

3.5 Veterinary, avian and femorotibial joint physical therapy principles

Veterinary physical therapy (physical rehabilitation or rehabilitation, physical therapy) aims to restore, maintain and promote optimal function, optimal fitness, wellness and quality of life related with motion disorders (Levine et al. 2005). Physical therapy is applied to treat patients with chronic osteoarthritis, to promote postoperative recovery or conservative management of orthopedic or neurologic patients, to treat severely debilitated patients, to allow interaction with oncology patients, to enhance condition, strength and performance in athlete animals, to aid weight loss and finally to promote bonding/obedience in family pets (Knap et al. 2007).

Currently, more physical therapeutic modalities have been developed and therefore complex protocols facilitate optimal progress and outcome of a therapeutic strategy. The later may be consisted by cryotherapy, heat or hyperthermia, therapeutic ultrasound, neuromuscular electrical stimulation (NMES), massage, passive range of motion (PROM) and stretching, and finally therapeutic exercise (standing and balancing exercises, hydrotherapy, and swimming). Of great importance is to frequently monitor and evaluate the progress of the individual patient and readjust therapeutic procedures according to the results.

In avian medicine, the importance of rehabilitation was first stressed for wild raptor casualties (Martell and Redig 1985). These were perceived as “athletes” and therefore exercise and evaluation protocols prior to final release were developed (Chaplin 1989; Chaplin et al. 1993; Martin et al. 1993a). By contrast, in the exotic avian practices, physical therapy has only been addressed sporadically (Cooney and Mueller 1994; Pollock 2002; Echols 2006). Modalities included passive range of motion (PROM) and therapeutic exercise in terms of active assisted range of motion (AAROM) and active range of motion (AROM) (Martin et al. 1993a), while recently more sophisticated modalities such as low-level laser, therapeutic ultrasound and foam pad have been proposed (Turner et al. 1989; Gan et al. 1995; Wimsatt et al. 2000; Zehnder et al. 2007).

Most commonly the avian physical therapy plans were addressed to postoperative rehabilitation of wing problems. A specific plan for the avian femorotibial joint has not been submitted. In the canine patient with total stifle luxation or cruciate ligament rupture, treated with arthrodesis or external skeletal fixator, the postoperative plan includes massage, immediate PROM with emphasis in extension, cryotherapy and NSAIDs. Control AROM (leash walks) and aquatic therapy (underwater treadmill, swimming) could start the first two weeks after surgery, while endurance and strengthening activities may be initiated between the fourth and sixth weeks. A near full recovery may be expected twelve to sixteen weeks after the therapy initiation (Davidson et al. 2005; Knap et al. 2007).

Manual therapy comprises the main method of gaining the range of motion (ROM) and is indicated for pain and loss of motion secondary to neuromusculoskeletal dysfunction. Mobilizations are passive movements that are oscillatory or sustained stretch performed in a manner that the patient could prevent the motion. Maitland described four grades of mobilization (I-IV) and a manipulation (grade V mobilization) (Table 5). Generally, when ROM is decreased due to pain, mobilizations I –II should be applied, while if ROM is decreased due to stiffness mobilizations of grade III and IV are advised. For the restoration of the femorotibial joint primary motions the cranial glide, the physiologic flexion, the caudal glide and the physiologic extension exercises have been proposed (Saunders Gross et al. 2005).

Table 5: Maitland mobilization grades (Saunders Gross et al. 2005)

Grade	Explanation	Pain occurrence
I	Small-amplitude movements with 3-4 oscillations per second	No
II	Large-amplitude movements with 3-4 oscilations per second	No
III	Large-amplitude movements perfomed three to four oscillations per second at the end of Range of Motion	Slight discomfort
IV	Small-amplitude movements perfomed three to four oscillations per second between the starting point of resistance and the end of the Range of Motion	Slight discomfort
V	Sudden passive unprevented movement at the end of available Range of Motion	

3.6 Aims of the study

As prior indicated, there is little information regarding luxation management, especially of the stifle, in avian patients. The few cases that have been described are limited to psittacine and raptor species. Moreover, although new methods have successfully been applied and developed, these were mainly applied to pet birds where arthrodesis could also be a viable solution. It should be noted that the promising use of hinged linear skeletal fixators (HLESF) in small mammals have not been tried in avian luxations. Additionally, the recent successful use of the FESSA fixator, in long bone fracture management, has not yet been tested in luxation management as a linear transarticular ESF.

The primal aim of this study was to evaluate the use of FESSA fixator in stifle luxation management in pigeons. The light-weighted FESSA offers a hinged transarticular model, which allows gradual dynamization and early physiotherapy, in benefit of a full functional recovery of the affected leg. The effect of the early physiotherapy and the contribution of the hinged, linear, transarticular FESSA model will be discussed in comparison to the classical fixation and physiotherapy methods.
The ultimate goal would be to provide the avian clinician with a useful comparative compilation of information concerning avian femorotibial joint anatomy and kinematics, avian luxation prevalence and fixation techniques (focused on femorotibial joint) and the FESSA system use as well as a new practical and affordable option for stifle luxation repair in avian species

4 Animals, Materials and Methods

4.1 Pigeons

The pigeons used in this study were captured during a population control programme in the city of Zurich. The interventions were evaluated and approved by the cantonal Animal Care and Use Committee and licensed under number 144/2007.

4.1.1 Quarantine and acclimatisation phase

The eight adult individuals selected for the experimental phase had to spend a three week acclimatisation phase in their new environment, which also served as quarantine. During this period, the birds were weighed, ringed and observed daily for signs of local or systemic disease. All individuals received a full clinical examination, with emphasis on the musculoskeletal system and whole body radiographs (in ventrodorsal and laterolateral projections) were obtained. Finally, faeces and blood samples were collected and submitted for parasitologic (*Eimeria, Capillaria, Heterakis, Ascarids, Stongyllids, Cestodes*), bacteriologic (*Salmonella* sp.), haematologic and serologic examinations for Newcastle disease (PMV-1). All birds tested negative for Salmonella and PMV-1., while due to the presence of Coccidia (*Eimeria* sp), the birds were collectively treated with Totrazuril (Baycox®, Bayer, Provet AG, Lyssach, CH) at a dosage of 75mg/L, SID, PO in the water for five consecutive days. After the monthly recheck, *Eimeria* sp and *Capillaria* sp were recovered and therefore the birds were treated with Totrazuril (Baycox®, Bayer, Provet AG, Lyssach, CH) (30mg/kg, SID, PO) and Ivermectine (Ivomec® 1%w/v, Merial GmbH, Hallbergmoos, DE) (0,5 mg/kg, IM, SID) respectively (Pollock et al. 2005). Ivermectin was repeated after 14 days.

4.1.2 Husbandry

During the quarantine period, the bird group was held in an indoor aviary 100 cm x 240 cm x 200 cm. After surgery each bird was confined for the subsequent six weeks to a crate with measuring 42 cm x 42 cm x 58 cm; these individual crates were placed in indoor holding pens (4 crates per pen) and stacked in such a way that the mesh doors faced the larger indoor aviary where a substitute flock was held, in order to facilitate a minimum of social contact. A heat lamp was installed in both the aviary and both of the holding pens. Additionally, to preserve the normal circadian cycle, apart from natural light, artificial light was also provided. Every day the birds were fed ad libitum with a commercial pigeon pellet diet (UFA Geflügelfutter®, UFA Ag, Herzogenbuchsee, CH) and a vitamin D-calcium mix (Nutrobal®, Vetark Professional, Winchester UK). To enhance the pro-vitamin D metabolism and its effect to the calcium deposition a UV-light exposure was ensured by a UV-lamp (Osram Vitalux 300W ®, Osram AG, Winterthur-Töss, CH), placed in 20 cm distance from the perch, and switched on for half hour per day. Food, grit (Sand for Birds®, Mauser AG, Thun, CH), and drinking water were available at all times. Experienced animal care personnel observed and secured the welfare of the birds. Moreover, the birds were inspected daily by a veterinarian for signs of general disease and especially for complications such as bumblefoot and osteomyelitis.

4.2 Materials (Surgery)

4.2.1 General

Excluding the specified fixation materials, common orthopedic, and surgical equipment was used for this study such as mosquito and drape forceps, scalpel No 15 and scalpel holder No 3, needle holder, haemostatic clips, blunt and sharp scissors, mini retractors and anatomic forceps. A microsurgery kit (S & T®, S & T AG, Neuhausen, CH) with haemostatic clips and various scissor and forceps types, were used. The pin placement and the cortical screw fixation was performed with a mini hand chuck (IMEX™ Veterinary Inc, TX, USA provided by Medical-Solution GmbH, Steinhausen, CH), a small pin cutter (max ∅ 1,5 mm) and a mini screwdriver (Synthes GmbH, Oberdorf, CH).

4.2.2 FESSA fixator and hinge

The fixator is made of stainless steel and different models are available with a diameter of 6 mm, 8 mm and 12 mm, for which Kirschner pins of up to 2 mm and 2.5 mm, respectively, may be used respectively. The length of the fixator varies from 30 mm to 200 mm, and linear or angular models are available. A system of screws and holes is used to attach the pins in the tube, and replaces the connecting rod and clamps used in other external fixator systems. Allen keys are supplied to fit the system, and the use of a low-speed drill or a mini hand chuck is recommended for precise pin placement. The minimum distance between pins is 2 mm. The pins may be placed either perpendicularly or, by exiting through the neighbouring hole, at an angle of approximately 30°. The hinges (6mm and 8mm) are comprised by two separate parts, which are connected to each other with a screw. This screw has a hexagon head filling to pass with an Allen key. The interim round surface of the two parts is roughened with a trailing edge or saw-like margin. The elongated edges are secured to the appropriate FESSA tube with screws. The maximum angle that could be achieved is 180^{o}, whilst the smallest around 40^{o}.

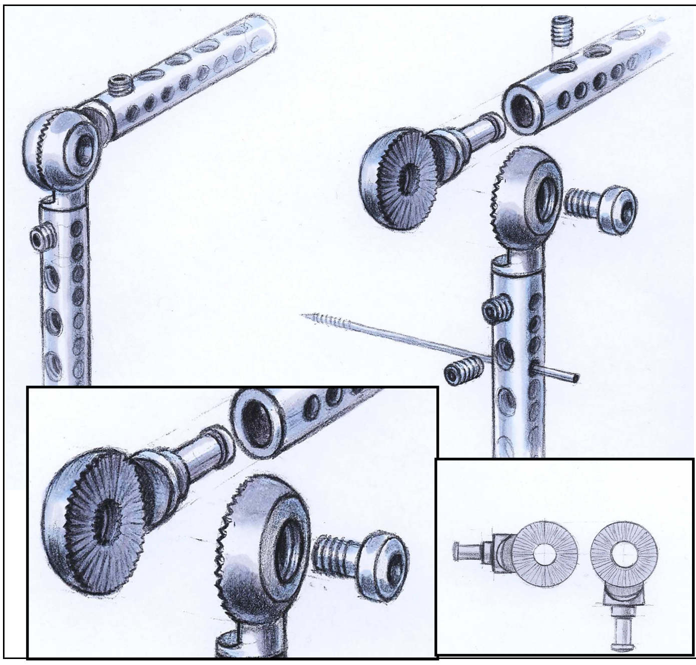


Figure 14: The FESSA hinge and the components of the hinged linear external skeletal fixator (HLESF). In the magnified pictures, details of the internal part of the hinge and its trailing periphery are shown. The two hemi-parts are fixed together with a hexagonal screw and to the FESSA tubes with a normal pin screw. (Drawing by M. Haab)

In the present study, a 6mm FESSA hinge (Veterinary Instrumentation Ltd, Sheffield UK) was fitted to two 6mm x 31 mm FESSA tubes M3 (Medical-Solution GmbH, Steinhausen, CH) to form a movable, transarticular external fixator (see Fig. 14). The whole hinged system weighted 10 g. The fixator was stabilised in femur and tibiotarsus with two, positive threaded pins (Miniature IMEX™ INTERFACE™ Fixation Half-pins 0.035", ∅ 0.9 mm x 75 mm provided by Medical-Solution Gmbh, Steinhausen, CH) per bone. This was the smallest available size of external fixation pins, chosen to reduce the possibility of iatrogenic fractures in the thin and brittle avian long bone cortices (Bennett and Kuzma 1992).

4.2.3 Artificial lateral collateral ligament

For the substitution of the collateral ligament, a cortical bone screw and a nylon monofilament non-absorbable suture were selected.

The particular type of suture material has been recommended by many small animal and avian surgeons (Roush 1980; Harcourt-Brown 1996; Denny and Butterworth 2000; Jaffe et al. 2000; Demirkan and Kilic 2003; Villaverde et al. 2005; Piermattei et al. 2006). For the present study, the 3-0 metric Prolene ® (Ethicon Inc, Sommerville, NJ, USA) was selected. PROLENE® is a sterile, monofilament, non absorbable suture consisting from isotactic, crystallic stereoisomer of polypropylene.It is generally recommended for suturing the soft tissues in neurosurgical, ophthalmologic, and cardiovascular surgery. The criteria for its selection were the availability, the cost, the lack of known reactions, and its use in delicate soft-tissues. Furthermore its blue colour contributes to accurate use and detection through the soft tissues. The chosen cortical bone screw (∅1.5 mm and 7mm long by Medical-Solution GmbH, Steinhausen, CH) is manufactured from high purity and quality mixture of chromium-nickel-molybdenum and stainless Steel 1.4441 in DIN 7443 and it was certified by German manufacturers (CE 0123). A screw of similar size and diameter was also used in luxations; in pigeons (Villaverde et al. 2005) and a psittacine (Jaffe et al. 2000). Cortical bone screws –with or without washer- provide stability and act as artificial pole to create the artificial band as proposed by small animal textbooks (Denny and Butterworth 2000; Piermattei et al. 2006).

4.3 Experimental study

4.3.1 Habituation with surgical approach, equipment and fixation techniques on dead pigeons

The main aims of this phase were the habituation to the fixation materials, the development of the surgical approach, and the luxation technique. The subsequent correction and fixation, as well as photography through visual magnifier, were also exercised. One of the important goals of this stage was to simulate the conditions of a regular operation mechanising the operation acts, to detect any possible difficulties in the pre-chosen techniques, and to overcome any other unforeseen obstacles.

Regarding the surgical approach two techniques were tested. At first, a full length incision from the proximal femur to the second third of tibiotarsus was tried in terms of time saving (arthrotomy and full exposure of femur and tibiotarsus). The direct visualisation of the long-bones was thought to help the accurate introduction of the pins. This method was soon discarded as it proved more time consuming and with more possible disadvantages such as the large suturing surface (harbouring a higher risk of postoperative infection, more time to suture, possible skin irritation or generalised discomfort of the patient), the poor accessibility of the cranial articular cavity (usually the incision was lateral instead of parapatellar) and finally the possible contracture of the major muscle units in the time between the initial arthrotomy and the pin fixation.

A second technique was evaluated and finally adopted, as it was quicker and eliminated the disadvantages of the previous-mentioned technique. The idea of the second technique consisted of a separate parapatellar incision to produce and fixate the model stifle luxation and subsequent stab incisions, in pre-selected points of the femur and tibiotarsus, to insert the pins. The detailed surgical approach will be given in a subsequent chapter (see Fixation method No 4.4.1.2).

For the additional attachment of an artificial collateral ligament to stabilise the femorotibial joint the method was decided after three techniques had been tested. The first was the passage of a single-strand suture through pre-drilled tunnels in the femoral condyles and the proximal cnemial crest as proposed by various authors (Roush 1980; Holz 1992; Fukui 2005). For the second method a cortical screw was placed in the lateral femoral condyle and the nylon suture fixed around its head, after passing through a hole in the proximal cnemial crest as described by Jaffe et al (2000). A third method applied by Villaverde et al (2005) as described in small mammals textbooks (Denny and Butterworth 2000; Piermattei et al. 2006) was similar to the previous with the only difference that the suture passed through a tunnel burrowed through the fibular head. This last technique was chosen for this study, because was easier to be idetified, safer for the tibiofibular syndesmosis and provided increased stability

4.3.2 Determination of the appropriate femorotibial luxation technique

From the stifle luxation cases described in the literature (see Table 6), it seems that a concrete pattern of luxation could not be foreseen (Bowles and Zantop 2002).

The changes and impact, which affect the ligaments of the avian femorotibial joint, suffering from the syndrome of “knee ligament failure” have thoroughly been described in dyschondroplastic broiler chickens (Duff 1985; Duff 1986a; Duff 1986b). According to these findings, the caudal cruciate ligament was more commonly ruptured, while the cranial cruciate was always intact (Duff 1986b). Moreover, an association between lateral collateral ligament and caudal cruciate ligament failure could be implied (Duff 1986b). Degenerative lesions and age related factors precede ligament rupture, while the cruciates were ruptured frequently close to their bony attachments (Duff 1986a). Regarding the collateral ligament derangement, abnormalities, such as active osteoclasia, fibrovascular tissue, and fibrin thrombi occurred frequently in the lateral collateral ligaments (Duff 1988). In pet birds, Holz (1992), Clipsham (1991a) and Bennett (1998) have reported rupture of collateral and cruciate ligaments in a stifle luxation, while solely hyperextension was also noticeable (Jaffe et al. 2000). Additionally, total rupture of collateral and caudal/cranial cruciate ligaments, resulting in a total femorotibial luxation, has been documented in species other than psittacines or domestic fowl (Fukui 2005).

Table 6: Reported stifle luxation type in birds

Citation	Luxation type	Ligament status
(Donato 2000)	Medial caudal of tibiotarsus (90^o)	Collateral and cruciate ligaments severely stretched
(Jaffe et al. 2000)	IV Medial patellar & 90^o tibiotarsal rotation	Stretched collateral but intact cruciate ligaments
(Bowles and Zantop 2002)	Craniomedial	Not referred
(Fukui 2005)	Medial craniocaudal	Full rupture of caudal, cranial cruciate and lateral collateral ligaments
(Holz 1992)	Craniolateral	Ligament rupture
(Rosenthal et al. 1994)	Craniolateral of tibiotarsus	Not referred
(Alievi et al. 2001)	Craniolateral of femur with 180^o rotation	Not referred
(Zantop 2000)	Medial luxation of tibiotarsus	Not referred
(Villaverde et al. 2005) experimental	Mediolateral	Collateral and femorofibular ligaments sectioned (exp)
(Harris et al. 2007)	Craniolateral	No
Chinnandurai et al 2009	Cranial and cranioproximal displacement of tibiotarsus with rotation	Rupture of cruciates (one case)
(Naldo and Samour 2002)	Mediocaudal	Not referred

Evaluating the above-mentioned data and also considering the commonest luxation aetiology (trauma after leg entrapment) it was assumed that *a mediocaudal luxation of the tibiotarsus is more prevalent* in companion avian patients and the production of such a model luxation (mediocaudal luxation with major craniocaudal instability) would serve the purposes of this study. This was achieved by incising the lateral collateral ligament and subsequently the cruciate ligaments (see also Methods).

4.3.3 Assessment of normal femorotibial joint angle and instant centre of rotation (ICR)

The successful application of a hinged external fixation depends largely upon the previous measurement of normal angle and the instant centre of rotation. It is important that the later is concentric with the isometric centre of the hinge in order to facilitate flexion and extension exercises of the joint.

Manual goniometry

Despite the fact that a method to access the normal standing angle in birds has recently been proposed for which the animals do not need to be handled (Bonin et al. 2007), the manual goniometry was chosen for this study due to its time efficacy. The goniometric measurements were performed as described by Knap et al (2007). One limb of the goniometer was placed along the long axis of the long bone proximal to the joint and the other along the long axis of the long bone distal to the joint. The centre of the goniometer was in the isometric point of the femorotibial joint. This method is the simplest and can be applied either with the animal (i.e. dog or cat) conscious or under sedation, without influencing the range of motion. Bonin et al (2007) found that in cockatiels (*Nymphicus hollandicus*) the mean femorotibial joint angle was $47^{o} \pm 1.3$ (in asymmetric, cranial view proposed as the most accurate for stifle angle assessment), while Villaverde et al (2005) immobilised the femorotibial joint in experimental pigeons in a functional angle of 60^{o} degrees.

Instant centre of rotation (ICR)

At present, there are no studies available proposing a special method or references for the determination of the ICR of the stifle joint in birds. Only recently some studies in canine patients appeared, suggesting that the ICR of a normal stifle is near to the joint articular surface of the femur and that there is no difference if measured in the same dead or alive dog (Ireland et al. 1986). A basic technique used to locate the ICR is the one based on the Rouleaux (1876) mechanic principles, determining the temporary centre of rotation (tICR) which approximates the ICR in small angles.

Due to its simplicity, this method was adopted for this study. Pre-selected reference points in the cranial (A) and caudal (B) femoral surface, as proposed by Selmi et al (2003), were used to locate the instant centre of rotation of the tibiotarsus in two experimental intact pigeons. Laterolateral radiographs were taken in full extension (180^o) and in 90^o flexion. Clamps were attached to the femur and tibiotarsus to ensure that the level of the two bones was parallel to the X-ray film and no axial rotation occurred. Additionally, the ray beam was centered to the supposed ICR, while the distance between X-ray source and joint was 100 cm.

The two radiographs (in extension and flexion) of the femorotibial joint were superimposed, using the tibiotarsus as reference point. The distance between the two corresponding reference points A and A' (Fig. 13) on the cranial femoral surface in extension and flexion, and B and B' on the caudal femoral surface in extension and flexion), were linked by a straight line. From the midpoint of these lines, perpendicular lines were drawn towards the centre of the joint. The point where the two perpendiculars meet is defined as the ICR.

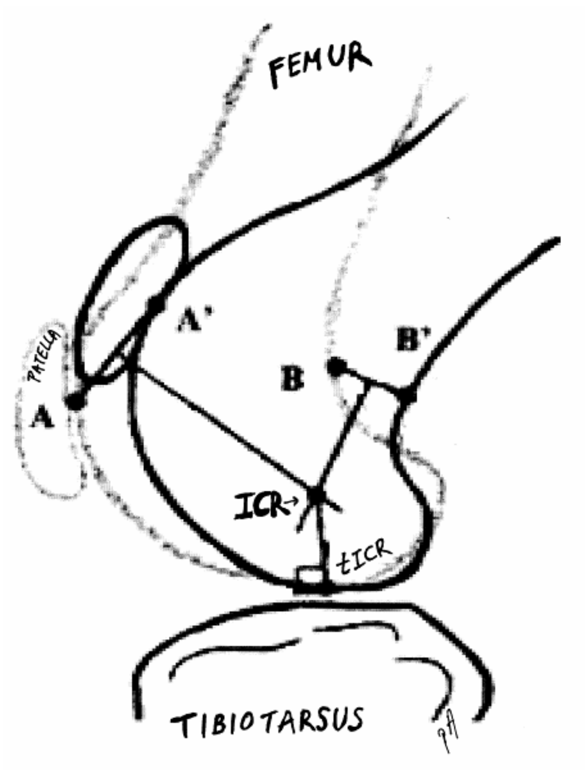


Figure 13: Schematic representation of the instant centre of rotation (ICR) in two superimposed radiographs taken in extension and in 90^o flexion. The ICR lies, where the midlines of the radiographic displaced points meet.

4.4 Fixation method

4.4.1 General

4.4.1.1 Anesthesia application and monitoring

Each bird was pre-medicated with butorphanol (Morphasol-4®, Graeub AG, Bern, CH) of a dose of 2 mg/kg (IM, SID), 15 minutes before induction with isoflurane (IsoFlo ad us vet, Abbott SA, Baar, CH). Additionally, every bird was rehydrated, administering lactated Ringer's (Fresenius Kabi AG, Stans, CH) subcutaneously in the groin, in two equal doses of 5 ml. Carprofen (Rimadyl®, Pfizer, Graeub AG, Bern, CH 2mg/kg, IM, SID) and enrofloxacin (Baytril 5%®, Bayer, Provet AG, Lyssach, CH 15 mg/kg, SC, BID) were also administered preoperatively. A mask of suitable size was used to pre-oxygenate the bird for 1-2 minutes and then isoflurane was administered in concentration of 5% and an oxygen gas flow of 1L/minute through a closed circuit. A 20AT (2 mm) sized uncuffed endotracheal tube (Cole-type) (SurgiVet®, Smiths-Medical, Waukesha, WS, USA) was placed and isoflurane flow was afterwards lowered and maintained to 2.5% concentration with an 0.5 L/min oxygen flow.

The anesthetic monitoring included bispectral index (BIS XP®, Aspect Medical Systems provided by Anandic Medical Systems, Lausanne, CH) and, through a portable three polar monitor (BSM 2353K®, Nihon Kohden Corp., Tokyo, Japan), electrocardiogram (ECG) and heart rate, relative oxygen saturation (SpO2) and pulse rate, end tidal carbon dioxide pressure (ETCO2) and temperature via an oesophageal probe of a pulse oxymeter and a capnometer. A warm-water circulating heating pad was used to decrease heat loss and the risk of hypothermia.

4.4.1.2 Surgical preparation and approach

All birds were placed in left lateral recumbency. The right leg was aseptically prepared starting from the cranial dorsal area of the hip joint to the tarsal joint. The extremity of the leg was gloved and secured with an adhesive tape, while a second sterile glove, anchored with a drape forceps, covered the extremity after aseptical preparation and drape placement to provide the surgeon access to the most convenient angle and position. Feathers were plucked carefully in order not to disrupt the fragile skin. Adhesive tape (Transpore™, 3M Health Care, Neuss, Germany) was attached to the neighbouring feathers and in some instances feather edges were cut. After scrubbing with a chlorexidine solution (Hibiscrub®, Globopharm AG, 8700, Küsnacht, CH), a minimum quantity of alcohol was poured to the whole length and periphery of the right leg with emphasis on the knee. Sterile drapes with drape clamps defined the aseptic area.

Before the surgical approach, the leg was palpated and the lateral collateral ligament was located. A linear lateral parapatellar incision of 2 cm length was performed from the lateral femoral condyle to the fibular head with the joint kept in full flexion. Subsequently, the fascia lata and the articular capsule were incised to access the articular cavity. Finally, the patella was medially dislocated, with the knee in extension, to allow full view of the intra-articular structures.

4.4.2 FESSA fixation and artificial lateral collateral ligament (both groups)

After the articular cavity was accessed, the lateral collateral ligament was carefully incised. In this way, a medial rotation of the tibiotarsus (60^{o}) was possible. A small portion of the intra-articular fat pad was removed to provide view of the caudal and cranial cruciate ligament insertations, as well as of the menisci. The cranial cruciate was cut proximal to its tibiotarsal attachment using microsurgical straight-end scissors. Similarly, the caudal cruciate ligament was cut after exposure of its insertation, although in some cases, due to the small bird size, it was blindly “fished” and cut using a 22-G hypodermic needle (Terumo Europe NV, Leuven, Belgium). The needle was first directed from cranial to caudal and then mediocranially in order to elevate, stretch and finally disrupt the caudal cruciate, until satisfying craniocaudal “drawer“-movement was present. Special attention was given to leave intact the menisci or other important articular components (i.e. other ligaments, articular cartilage, fat, and synovial bursas)

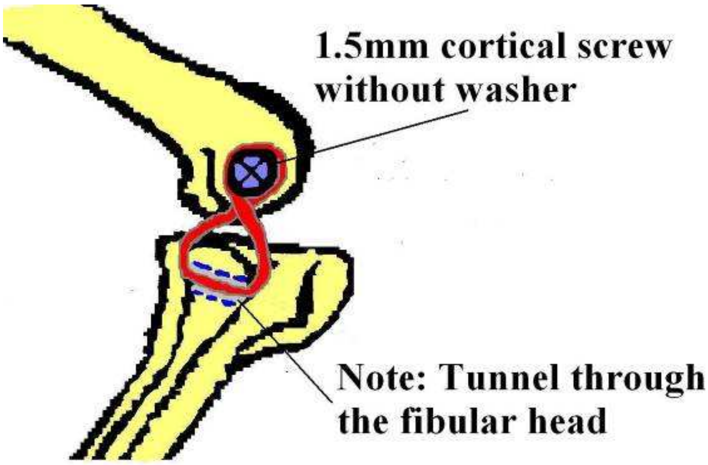


Figure 16: Intracapsular technique used in this study. A nylon suture was threaded through a tunnel in the fibular head and fixed on the lateral femoral condyle with a cortical screw.

To substitute the lateral collateral ligament, the unthreaded edge of a 1.2 mm positive threaded pin (Miniature IMEX™ INTERFACE™ Fixation Half-pins 0045”, ∅ 1.2 mm, 75 mm, Medical Solution GmbH, Steinhausen, CH) was used to manually drill a 7mm hole into the lateral femoral condyle, exactly proximally the insertion of the lateral collateral ligament. A second tunnel was burrowed through the fibular head (the proximal cnemial crest) with the help of a 20-G hypodermic needle (Terumo Europe NV, Leuven, Belgium). A ∅1.5 mm and 7mm long cortical screw without washer was inserted in the femoral hole. The nylon monofilament suture (Prolene 2-0, Ethicon Inc, Sommerville, NJ, USA) was threaded through the fibular tunnel, using the needle as guide, and looped around the screw head in figure of eight scheme. While the tibiotarsus was held in alignment and a functional 60^{o} angle, the suture was tied leaving the knot laterally and the screw was tightened. Afterwards, the articular cavity was inspected, flushed with normal saline (NaCl 0,9% Fresenius Kabi Norge AS, Halden, Norway) and the capsule was closed, in a simple or crossed interrupted pattern, with a 4-0 polydioxanone suture (PDS II, Johnson &

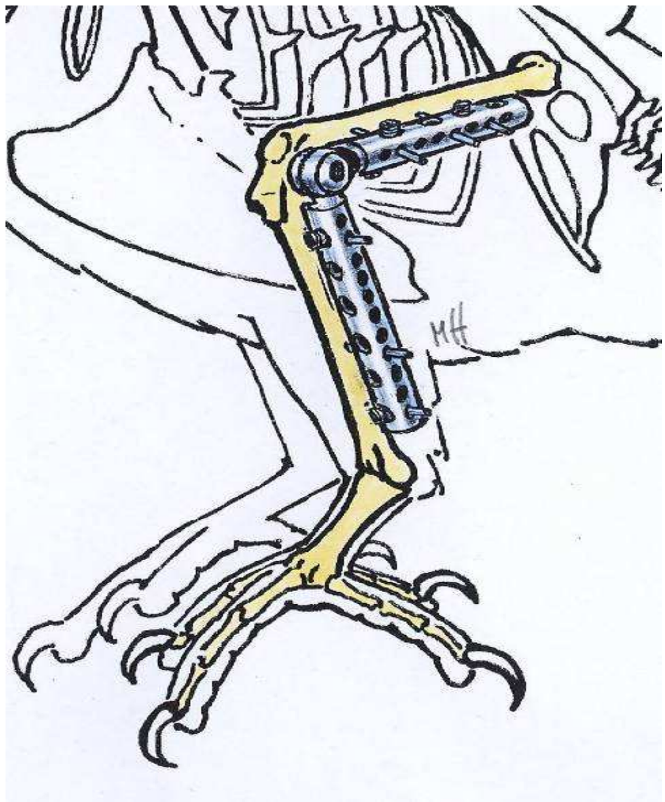


Figure 17: Depiction of the transarticular hinged linear ESF used for the reponition of the avian femorotibial joint in this study (Drawing by M. Haab).

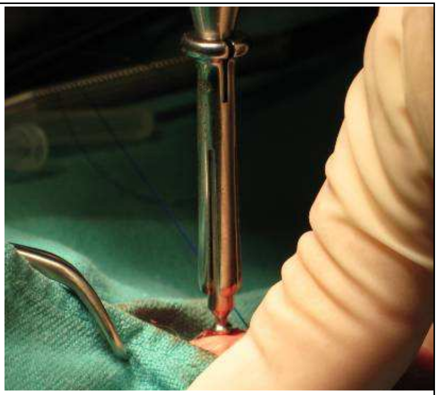
Johnson Int, c/o European Logistics Centre, St Steven-Woluwe, Belgium). In some cases horizontal mattress sutures was applied to burry and secure the screw head. The fascia lata and the skin were usually closed with four simple interrupted sutures, placing the first in the middle of the incision to relief tension and leaving a small gap distally to the lower suture as drainage.

The stabilization of the femorotibial joint took place with the placement of the hinged FESSA system. The pre-fixed (in 60^{o} angle) hinge was supra-impositioned to the supposed instant centre of rotation (ICR) of the joint, near the articular surfaces (this study, Ireland et al. 1986). After the selection of the suitable pin holes of the FESSA tube, and taking in account the cross-sectional anatomy of the avian femur and tibiotarsus - as well as the defined danger, hazardous and safe zones (Donato 2000) -, two stab incisions of 3 mm length were made on the skin of femur and tibiotarsus, with a No 15 scalpel blade as described by Kraus et al (2003). The soft-tissues were retracted with a mosquito forceps for the visualisation of the bone. Moreover, the tubes acted as guide for correct pin insertion The femoral pins were introduced to the cranial lateral surface of the mid-diaphysis and proximal femur, the latter in order to increase stability as cortical bone is indicated for its solidity (Denny and Butterworth 2000). In the tibiotarsus, the pre-selected points were located on the caudal 2/3 of the lateral surface of the mid-diaphysis and along the full length of the distal tibiotarsus (Donato 2000). A mini hand chuck (IMEX™ Veterinary Inc, TX, USA provided by Medical-Solution GmbH, Steinhausen, CH) was used to insert the mini positive-threaded pins (IMEX, 0035”, ∅ 0,9 mm, 75 mm, Medical Solution GmbH) and the FESSA screws and Allen key (Medical-Solution Gmbh, Steinhausen, CH) to stabilize them in the connecting bar. In general, the pins were fixed with the following sequence; proximal femoral, distal tibiotarsal, distal femoral and proximal tibiotarsal. The latter was used as simple Kirschner placed in 30^{o} to increase stability. The skin around the pins were left open (Kraus et al. 2003). Finally, the motility of the system was tested with flexion-extension moves and loosening the hinge to achieve full extension. Immediate post-operative radiographs (two projections) were used to assess the success of the technique or possible mistakes in ESF fixation.

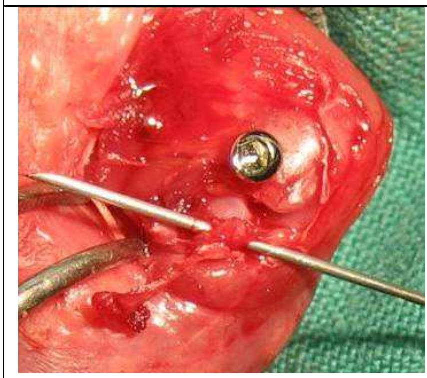
Figure 18: Pigeon right femorotibial joint. Surgical approach and sequence of fixing the artificial lateral collateral ligament and the FESSA hinged linear ESF

I) Parapatellar approach

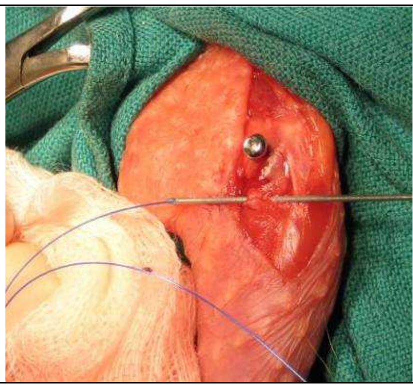
II) Drilling the condyle tunnel



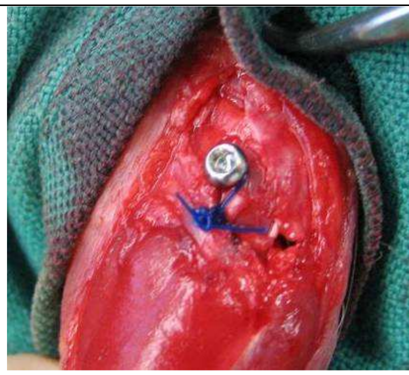
III) Inserting the bone screw



IV) Drilling the fibular head tunnel



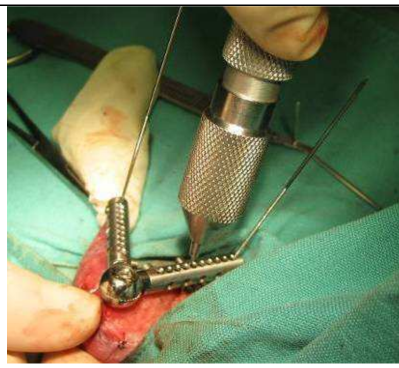
V) Passing the nylon suture



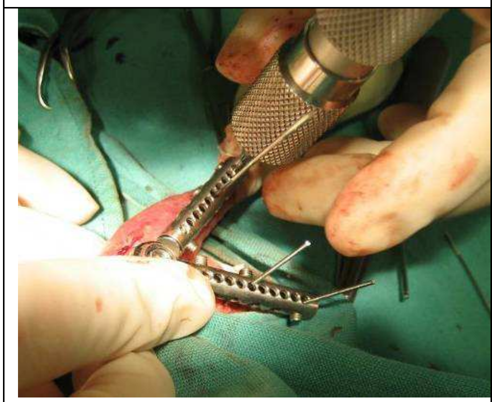
VI) Figure of eight knots; Artificial Collateral Ligament

VII) Closing the articular capsule

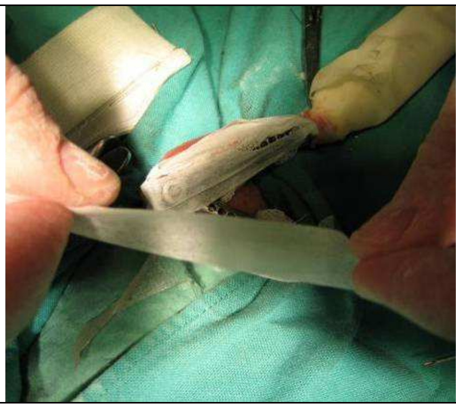
VIII) Skin closure



IX) Stabilizing the instant center of rotation



X) Stabilizing the FESSA system



XI) Bandaging the pin edges

XII) Final outcome

4.5 Post- operative care and complication monitoring

4.5.1 General

Special attention was given to the post-operative care as its importance for the outcome of orthopedic avian surgery has been stressed by many authors (Jenkins 1993; Cooney and Mueller 1994; Bennett 1997; Coles 1997; Redig 2001; Harcourt-Brown 2002; Pollock 2002; Kraus et al. 2003; Murphy 2006). Pigeons were post-operatively maintained for 15 hours in a warm, indoor facility confined in a small Pet-porter® (Petmate Int, Arlington, TX, USA), and then transferred to individual cages (see also Husbandry). During the first night an infrared lamp was provided. Each cage was equipped with an orthopedic “pillow”, made by a dipper stuffed with hay (Suedmeyer 1992; Cooney and Mueller 1994; Pollock 2002). Additionally, paper substrate, food, water and grit were available at all times. The decision to confine the birds for the whole period, instead only for a few days, was made in order to assess subjective control, to reduce stress and ease handling and to avoid intra-specific aggression caused by dominant individuals. A perch was not added until after the third week, to avoid unnecessary trauma (Pollock 2002). The cage floor and “pillow” were cleaned daily.

The whole ESF was bandaged, in a triangular shape, using gauze passed through the pins and under the tubes and hinge and taped with Micropore™ (3M Health Care, Neuss, Germany). Extra tape on the cut pin end protected the feathers and soft-tissues from injury. The bandage was inspected every day, changed every three days and finally removed after one week. For the first three days, a drop of diluted povidone iodine (Betadine®, Mundipharma Medical Company, Hamilton, Bermuda provided by Provet AG, Lyssach, CH) was poured on each pin tract daily. In cases, in which haematomas were evident an ointment with Heparinoidum (Hirudoiod®, Medinova AG, Zürich, CH) was applied locally. Analgesic medication (Rimadyl®, Pfizer, Graeub AG, Bern, CH) (2mg/kg, IM, SID) was administered for seven days (see also below) and antibiosis for five days (Baytril 5%®, Bayer, Provet AG, Lyssach, CH, 15 mg/kg, SC, BID).

4.5.2 Physical therapy method

Post-operative physical therapy of the orthopedic patient is crucial for healing and gain of normal limb function (Taylor 1992; Davidson et al. 2005). Moreover, the core of this study is the evaluation of the early physical therapy effect after joint surgery. The birds were randomly divided in two groups of four; the ***early physical therapy group (EPG***), (formed by individuals with code No 1,3,5,7), which started physical therapy the day after surgery and for the subsequent three weeks and ***the late physical therapy group (LPG)*** (formed by individuals with code No 2,4,6,8), which received physical therapy after three weeks of stabilization and subsequent ESF removal as proposed in previous studies (Rosenthal et al. 1994; Bowles and Zantop 2002; Villaverde et al. 2005). This group was also considered as the control group. Each bird received a total of *eleven sessions*, within three weeks postsurgically, under isoflurane anesthesia.

The overall physical therapy plan was elaborated to balance between well-accepted veterinary physical therapy principles and adjustments to the avian patient. Massage, passive range of motion exercises (PROM) and active range of motion (AROM) were applied (Martin et al. 1993a; Manning et al. 1997; Pollock 2002; Zehnder et al. 2007). The detailed plan is given in *Table 7.* Massage of thigh and gastrocnemius muscles was performed, prior to joint mobilization, using effleurage and pétrissage (Manning et al. 1997; Haltrecht 2000).

Manual therapy, aiming on joint mobilization, was mainly performed with mobilizations of grade II-IV, as recommended for canine stifle luxations and cruciate ligament ruptures by Davidson et al. (2005) and Saunders Gross et al. (2005). The *end feel*, the sensation imparted to the examiner at the end of the range of motion, was monitored although not systematically recorded. Manual mobilization of the rest of the pelvic limb joints (coxofemoral, intertarsal, metarsophalangeal) took place the last 2 minutes of each session. Active assisted range of motion (AAROM) has been described for birds recovering from wing problems (Martin et al. 1993a; Pollock 2002), while recently a foam pad was suggested for weight-shifting exercises (Zehnder et al. 2007). In the present study the AAROM was not direct and standardized. The combination of a mid-height perch, a pad of unequal surface and offering food and water on the floor, forced the bird to move in three levels using different joint angles through the day, especially after hinge loosening or ESF removal. Additionally, active coaxing to move twice a day contributed to walking, which was designated as the safest exercise in non-stress-susceptible patients (Pollock 2002).

Table 7: Femorotibial joint physical therapy plan in pigeons following experimental stifle luxation

Weeks		**1st**	**2nd**	**3rd**	**4th**
Selected Method	*Duration*				
Massage	1-2 min	1-2min	1-2min	1-2min	
Passive range of motion (PROM)		5-7 min	10min	10-13min	
i) Grade		I-II	III-IV	III-V	
II) Repetitions		20	40	Up to 40	
iii) Daily frequency		Once/d	Once/d	Once/d	
iv) Weekly frequency		Twice	triple	triple	
Active range of motion (AROM) (indirect)					
i) Soft mattress	24h	24h	24h	24h	
ii) Coaxing (daily frequency)	2-3min	Once/d	Twice/d	Twice/d	Twice/d (minim)
iii) ESF hinge loosen or removal					24h
iv) Perch					24h

4.5.3 Pododermatitis (bumblefoot)

Pododermatitis is a common complication of the plantar foot surface after hindlimb injury, occurring in captive raptors, waterfowl, poultry and psittacines (Coles 1997; Harcourt-Brown 2002; Helmer 2006). In pigeons it is occasionally seen (Harper 1996). The orthopedic patient does not bear weight to the injured/operated leg and therefore the unaffected leg supports the whole body weight. This induces pressure forces of the plantar foot and subsequent thinning and cracking of the skin, resulting in abscessation due to secondary infection. Many husbandry factors (i.e poor diet, overweight, limited exercise and hard perches) predispose to the disease (Harcourt-

Brown 2000; Harcourt-Brown 2002; Helmer 2006). The first sign is a mild, localized hyperaemic region progressing to swelling, abscess formation, and septic arthritis (Harcourt-Brown 2002). For this study, the five- grade scale proposed by Remple and Al-Ashbal (1993) and reviewed by Helmer (2006) was adopted (see Table 8).

Table 8: Pododermatitis grading scale in birds

Grade	Clinical Description (Helmer 2006)
I	Hyperemia, skin flattening of digital and metatarsal pads
II	Scab and mild swelling
III	Caseous abscess with marked swelling and pain
IV	Tendon infection with flexor tendon rupture, cellulitis of intertarsal joint
V	Osteoarthritis of the sesamoid bone of the digit II, septic arthritis tarsometatarsal-phalangeal joints

4.5.4 Osteoarthritis (Degenerative Joint Disease)

Osteoarthritis is commonly observed after joint injury or surgery in human and small animal medicine. In birds, it has been observed in young broilers (McNamee et al. 1998), turkeys (Huff et al. 2000), waterfowl (Degernes et al. 2007), raptors and pigeons (Rothschild and Panza 2006), but is generally considered to be rare (Harcourt-Brown 1996; Harcourt-Brown 2002). Eagles (*Aquila spp*) seem to be susceptible (Harcourt-Brown 2000). Additionally, *synovial chondromatosis,* not associated with osteoarthritis, has been recorded in raptor´s joints (Stone et al. 1999). Particularly in wild pigeons, osteoarthritis was present in a 9.8 % percentage of the examined museum specimens and located exclusively in the tarsometatarsal joint (Rothschild and Panza 2006). Most frequent causes of degenerative joint disease (DJD) in birds comprise intra-articular fracture, pin intrusion and primary joint trauma. The current study evaluated the presence of early DJD changes in pigeon stifle, by monitoring clinical pain and performing joint radiology 42 days following surgery.

4.5.5 Complications of external fixation

Great attention was given to monitor any fixation complications. These, according to Harari (1992) and Kraus et al (2003), could be classified in *pin tract infections* (i.e. soft-tissue sepsis/major pin tract infection, focal osteomyelitis, ring sequestrum), *fixator problems* (i.e. premature pin loosening, pin pullout/breakage/bending, unstable configuration, pressure skin necrosis, delayed bone union, iatrogenic fracture) and *soft tissue impalement* (neurovascular bundles, muscular tissue, tendons). The appearance of slight, serous fluid with minimal tissue inflammation and without or little patient discomfort is considered a sign for minor pin tract infection. In avian patients treated with ESF, the prevalent complications are osteomyelitis, non-union, premature pin loosening and instability (Meij et al. 1996; Hatt and Christen 2004; Hatt et al. 2007). This experimental study recorded only complications categorized as pin tract infections or fixator problems.

4.6 Surgical and healing assessment

4.6.1 Physical therapy data collection

To evaluate the effect of early physical therapy in the healing progress two main parameters were chosen; the thigh muscle circumference (TC) and the range of motion (ROM) of the femorotibial joint (Taylor 1992; Cooney and Mueller 1994; Knap et al. 2007). The later was divided in two subcategories “ROM in flexion” and “ROM in extension” as proposed by Monk et al (2006). The TC was measured at the midpoint on the long axis of the femur. Length of the femur was measured by use of a single standard 10-cm plastic ruler at the point half the distance between the greater trochanter and the lateral femoral condyle. The TC was measured by use of a single standard plastic non-elastic metric tape; measurements were obtained in triplicate with the anesthetised pigeons positioned in lateral recumbency and the tape measure was placed around the limb, as close as possible to the mid-thigh. Mean of three TC values was calculated and recorded. Additionally, the mid-thigh thickness

(TTh) was also measured with the same method (Fig 17). The ROM calculations performed as in normal goniometry described above (Knap et al. 2007). A single evaluator accomplished all measurements before, three weeks and six weeks after surgery, using a standardized protocol (Annex III).

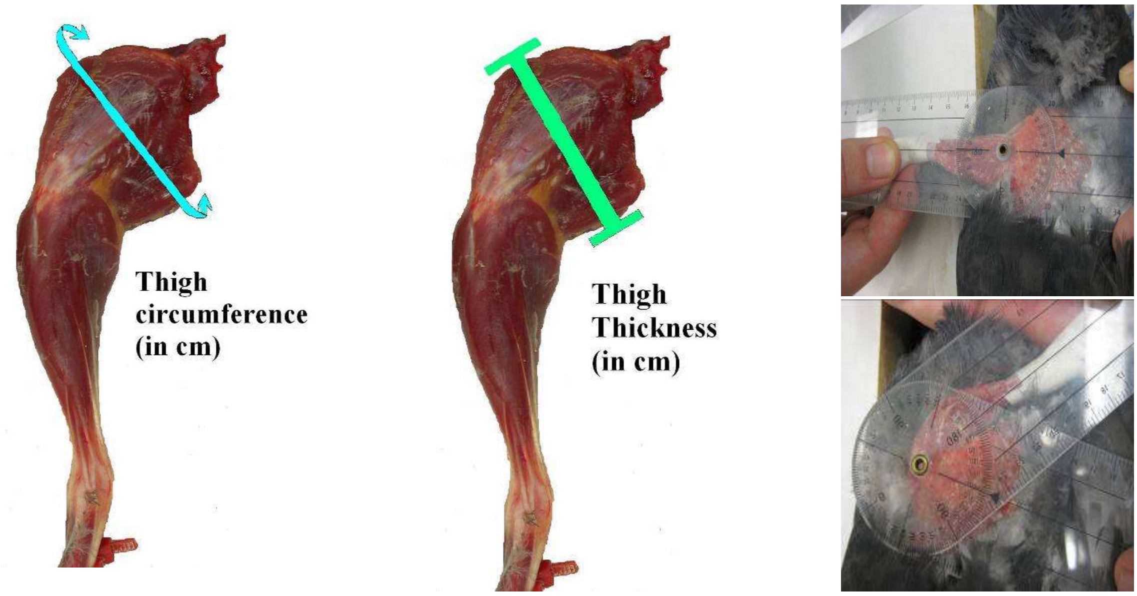


Figure 19: Physical therapy measurements in pigeons. Thigh circumference and thickness with a simple metric tape and goniometry in flexion and extension.

4.6.2 Radiological evaluation

The radiologic evaluation consisted by two sessions and was performed under isoflurane anesthesia. The first evaluation took place immediately after the end of surgery (Day 0) to control the proper placement of the FESSA and the other after six weeks of monitoring (Day 43), before euthanasia, to evaluate the healing process and any possible bone reactions or complications. In the first session two projections of the affected stifle were made (craniocaudal and mediolateral), while in the second session the healthy stifle was also radiographed. In all occasions a mammography plate and standard avian settings were used (40kV, 5.6 mA and 20ms)

4.6.3 Lameness protocol

Pigeons do not show pain in an obvious manner, as this behaviour is likely to attract predators (Livingston 1994). Yet, it is well accepted, that birds can perceive pain, as they possess neuroanatomical structures for nociception. Pain and lameness have been documented in a several common avian families like Anseriformes, Columbiformes, Psittaciformes (Machin 2005) and especially commercial poultry (Kestin et al. 1992; Reiter and Bessei 1997; Corr et al. 1998; Weeks et al. 2000; Weeks et al. 2002). Moreover, practioners are mostly capable to recognise acute pain in birds, but are less familiar with signs of chronic pain (Machin 2005).

Four pain scales have been used to assess pain in animals. The Simple Descriptive Scale (SDS), the Visual Analogue Scale (VAS), the Numerical Rating Scale (NRS) and lately the Multifactorial Pain Scale (MFPS). According to Dobromylskyi et al (2000) and Firth and Haldane (1999) the Multifactorial Pain Scales (MFPS) are more sensitive and subjective compared with other methods (MFPS > VAS ≥ NRS >SDS). Furthermore, Gentle (1992) suggests that pain detection assessment needs both behavioural and physiological measurements. So far a standardized pain scale has not been established for birds. A species-specific approach should be followed, if a pain scale is to be developed, as there is a great inter-species variation in clinical pain signs (Murphy 2006). The protocol formed for the purposes of this study is a merged version of two numerical rating scales (see Annex III); the Bristol Scoring System formulated for broiler lameness by Kestin et al. (1992) and the Anderson et al scale, was modified by Hatt et al (2007). The later has been used to evaluate lameness following orthopedic surgery in a study, which included pigeons (Hatt et al. 2007).

4.6.4 Euthanasia and post-mortem examination

After a 6-week period, the birds were sacrificed and both femorotibial joints were prepared for further histological analysis. Euthanasia was performed using a high concentration solution of pentobarbitalum natricum (Esconarkon ad us.vet, 300mg, G.Streuli & Co.AG, CH) administered intravenously or intraperitoneally under general anesthesia. Before euthanasia, a final orthopedic examination was performed (after removal of the HLESF in the EPG), focusing on the detection of drawer movement, rotation and joint instability. A subsequent post-mortem examination of both femorotibial joints, keeping the damage of articular structures at a minimum, was performed and findings were recorded in detail (see Annex IV). Additionally, synovial fluid was drawn from both joints immediately after death and after quick evaluation of the physical characteristics (see Annex IV), a smear for cytology was prepared and stained with Modified Wright's stain, as proposed by Campbell and Ellis (2007). To establish species specific criteria two intact pigeons were also examined as controls.

4.6.5 Histology

For the histologic preparation, muscles were fully detached from the bone, paying special attention to the ligament insertions. The right and left femorotibialis and gastrocnemius muscles of each pigeon were fixed in 4% formalin solution and submitted for routine histology to detect atrophy, hypertrophy and morphological changes. After longitudinal and transverse section of the middle muscle belly part, the respective samples were embedded in paraffin and stained with haematoxylin-eosin stain. The lesions per muscle, the centralization of nuclei, the perivascular fat tissue as well as presence of possible inflammation and fibrosis were recorded (see Annex V). Additionally, muscle fibre morphometry was performed selectively to indicate possible atrophy. The diameter of 20 fibres (per muscle and pigeon) was measured and their mean diameter value (per muscle and pigeon) was compared with a range derived from the same measurements in two intact pigeons. This was applied to two pigeons (one from each group) only, choosing individuals with the most significant clinical differences.

After separation of the distal femur and the proximal tibiotarsus, the whole femorotibial joint was fixed in 4% formalin solution and was submitted for further analysis (Fiechter 2005). After standard histological dehydration processing with different concentrations of ethanol and defatting in xylene, the joints were embedded in poly-methylacrylate. Afterwards two longitudinal thick slides (from the midline of each condyle) and one thin slide (from midline of intercondylar groove) were either stained with tolouidine blue and/or haematoxylin-eosin and van Kossa/McNeal. A modified Mankin protocol was used to evaluate degradation changes in the articular cartilage and the remodelling of the subchondral and the trabecular bone (Mankin et al. 1971) (see Annex VI). Four areas were evaluated namely the central part of the femur, the peripheral part of femur (cranial and caudal), the central part of tibiotarsal joint and finally the peripheral part of tibiotarsal joint (cranial and caudal). Presence of amyloid concentrations (as described by Stone et al 1999), osteophytes and improper stabilization (ongoing luxation) were evaluated. As osteophytes were characterised areas of bone formation, outskirting the normal margin line of fenur and tibiotarsus. Findings were recorded with a Leica M420 microscope (Leica ® DMR, Leica Instruments GmbH, Nussloch, Deutshland).

4.6.6 Statistical methods

Mean values of three independent measurements for ROM in flexion, extension, thigh thickness and circumference (pre-operatively, after 3 weeks and after 6 weeks period) were calculated with standard deviation (±SD). For scale parameters (weight, ROM and thigh measurements) with normal distribution, according to the Kolmogorov-Smirnov test, the Independent Sample t-Test was used to compare groups. Evaluation of nominal parameters (ESF complications, lameness, pododermatitis, perch use and histology) took place performing the non-parametric Mann Whitney U-test. To compare different parameters from different time points, serial paired t-tests with Dunn-Sidak adjustment for multiple testing were used. To correlate different parameters (weight-pododermatitis, lameness-pododermatitis), Spearman's rank correlation analysis was used. All analyses were performed using SPSS 16.0.1 (SPSS Inc., Chicago, IL, USA). The significance level was set to 0.05.

5 Results

5.1 Surgical technique and FESSA application

5.1.1 Surgery and anesthetic recovery

The mean surgery time was 124±22 min and the total anesthesia time was 181±33 min (see Annex VII). The delay was caused by pre-surgical measurements. In all birds surgery and anesthetic recovery were uneventful. The application of the cortical screw as well as the FESSA system was judged satisfactory in six cases with respect to the ICR and the system's motility for physiotherapy, whilst in two cases the hinge position appeared not optimal (Bird No 2, No 3) (see also 5.2) An iatrogenic luxation of the fibular head occurred in one case (Bird No 2). In another case (Bird No 5) the tibiotarsal pin insertion site was considered critical, since the distance between the exit points in the contralateral cortex of the two pins was less than 1mm (Fig. 20B).

5.1.2 External skeletal fixation complications

Only minor complications, regarding ESF, were observed and were not considered of importance to the outcome of the study (see Annex VIII). In six animals a minor pin tract infection, was detected for two to three days, following surgery. Bandage changes every two days and a drop of diluted iodine povidone solution in the pin insertion were applied successfully. In two cases, post-operative mild swelling occurred in the proximity of the femoral pin sites. A single case of each of the following minor complications was also observed: femoral pin holding screw loosening (Bird No 5), tibiotarsal haematoma (post-surgical) (Bird No 5), intra-articular haematoma (physical therapy phase) (Bird No 6) and pre-mature pin loosening during FESSA system removal (Bird No 5). The latter occurred during the fifth week in the EPG.

5.2 Diagnostic imaging

No abnormal radiographic findings were seen either at the projections of the third or the projections of the sixth postoperative week, except for bird No 2, in which the cortical screw seemed to have been loosened and laterally migrated (see Fig. 20C). Inaccurate ICR was detected in Bird No 2 and No 3 (Fig 20A). This fact did not have any impact because one case belonged to the LPG (only stabilization Bird No 2) while in the other case almost normal extension could be achieved (170-180^{o}) (Bird No 3).

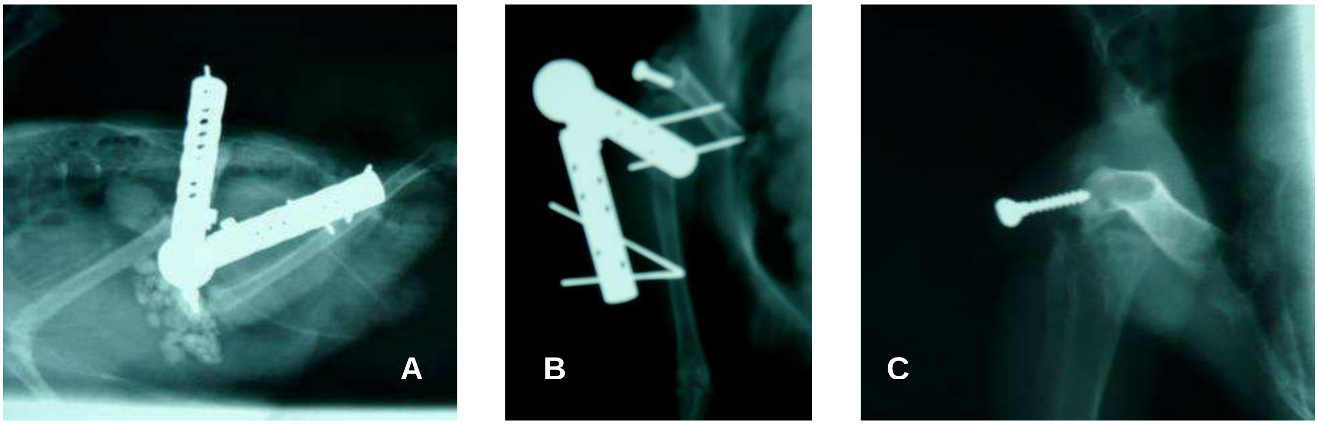


Figure 20: Radiographic findings. (A) Laterolateral view of the right hindlimb (Bird No 3) with inaccurate instant centre of rotation (ICR) position. (B) Craniocaudal view of the right hindlimb (Bird No 5) with inappropriate pin insertion in the tibiotarsus (pins too close). (C) Craniocaudal view of the right femorotibial joint (Bird No 2) presenting bone screw loosening laterally.

5.3 Healing progress

5.3.1 Goniometry (ROM)

Goniometry measurements, expressed as mean Range of Motion in flexion and extension, are presented in Annex X. Pre-surgically the overall mean ROM in flexion was measured as $31.5^o \pm 1.5^o$ and in extension as $179.9^o \pm 0.1^o$. The therapeutical aim was to re-attain these flexion/extension standards. After three weeks both groups collectively showed similar mean values in flexion and extension, but finally after six weeks the EPG gained more degrees ($36.8^o \pm 12.5^o$ and $140.3^o \pm 15.5^o$), numerically differing 3^o and 17^o from the respective values of the LPG; however, the differences between the groups were not significant. Additionally, the progress from the third to the sixth week was greater in the EPG. In this period the group gained $10.8^o \pm 12.4^o$ in flexion and $10.9^o \pm 14.9^o$ in extension, whilst for the same parameters the LPG gained only $2.3^o \pm 8.7^o$ and $7.0^o \pm 12.7^o$. Again these differences between the groups were not significant. The deviation from the normal ROM limits was present in both groups and the post-surgical acquired ROM only partially fulfilled the functional criteria of the species (see Annex II).

5.3.2 Thigh muscle measurements

The overall mean thigh muscle circumference pre-surgical was 5.30 ± 0.17 cm (5.35±0.24 cm in EPG and 5.24± 0.07 cm in LPG) and the respective value of thigh thickness 2.55± 0.21 cm (2.62± 0.25 cm in EPG and 2.48± 0.17 cm in LPG). Both groups presented the same pattern in TC with a 0.5 cm increase till the third week and a 0.3 cm drop until the sixth week. On the contrary, TTh showed a mean 0.31 cm reduction the first three weeks and a subsequent reduction of 0.08 cm (2. 23± 0.21 cm) until euthanasia in the EPG, whilst in LPG an initial mean reduction of 0.47 cm was followed by a 0.11 cm increase in the sixth week (2.12± 0.27 cm). The same measurements in the left thigh, at the day of euthanasia, produced a comparable result in TTh (2.87± 0.16 cm and 2.84± 0.16cm) and a 0.13 cm mean difference in TC between the groups. There was no statistically significant difference between groups (see also Annex XI). Differences between the left and the right leg were tested within each group. In both groups, there was no significant difference in the circumference between the right and left leg (paired t-test; EPG $p=0.507$, LPG p=0.207); in contrast, the left thigh had a higher thickness than the right in both groups (paired t-test; EPG p=0.014, LPG p=0.006).

5.3.3 Lameness

Lameness was detectable in all birds immediately after surgery with a high ranking (grade 4 or 5), which progressively decreased to grade 2 within 24 days (see Annex XII). Stability in healing progress or slow progress was observed between the second and fourth post-surgical weeks, with the birds presenting a score between grade 4 and grade 3. The quickest progress occurred in Birds No 1, 7, 8, and the slowest in Bird No 5; the latter did not actually achieve a "full" grade 2 scoring until euthanasia.

5.3.4 Pododermatitis

Pododermatitis (bumblefoot) was present in all birds, despite the preventative or therapeutical measures (see Postoperative Management). Early signs (Fig. 21) were observed at the end of the first week post-surgically, and until the sixth week all birds had acquired a grade I pododermatitis on both feet. Variation in the starting point of pododermatitis and leg first affected (right, left or both), was evident without presenting a consistent pattern (see Annex XIII). In three birds (No 5, 6, 8) pododermatitis appeared during the end of the first post-operative week, two more

Figure 21: Pododermatitis in pigeons: Grade I pododermatitis (A), exfoliating dermatitis (B) and foot pads (C).

birds (No 3, 4) presented signs during the second week, one bird (No 2) during the fifth week and the remaining two birds (No 1, 7) during the sixth week. Sings of pododermatitis occurred first on the untreated (left) leg with exception of bird No 7, where it occurred first on the right side. In bird (No 5) pododermatitis shifted from left to right in the second week. Pododermatitis was managed conservatively with intense feet hygiene (cleaning with warm saline) and footpads (see Fig. 21C) to reduce the pressure and facilitate weight shifting. The first two postoperative weeks antibiotics and analgesia was also beneficial.

5.3.5 Perch use

A perch in the mid-height of the cage was added after three weeks, at the time of hinge loosening in EPG and FESSA removal in LPG. One bird (No 1) perched immediately, four birds (No 2, 3, 4, 7) within the first week and the rest (No 5, 6, 8) within 15-21 days after the day the perch was added. Five of the birds used both feet (No 1, 2, 5, 7, 8,) the day they perched, two (No 3, 4) after four and two days respectively and one (No 5) consistently only used one leg all the time.

5.4 Femorotibial joint post mortem and synovial fluid examination

During the orthopedic examination (ante-mortem on the day of euthanasia) none of the birds of both groups presented positive drawer movement or tibiotarsal rotation. In post-mortem examination of the stifle joint, two birds (Birds No 1, No 3) presented with a fibrotic articular capsule only, while all the other birds (No 2, 4, 5, 6, 7, 8,) presented with fibrotic and also thickened capsule. The screw and suture material was in place with no alteration or displacement in most of the birds. Only in one individual (Bird No 2), the screw was loose and had migrated laterally, out of the articular capsule, though it was held in place due to fibrosis. After screw removal, no

Figure 22: Excessive callus formation in tibiotarsal pin insertion point (scale in centimetres)

rotation or other motion was present in the joint, with the exception of one case (Bird No 1) that presented with slight medial tibiotarsal rotation (see Annex XIV). The main finding in all pigeons was the excessive callus formation in the pin insertion point (see Fig. 22). The two intact control pigeons showed uniformity in post-mortem findings. In the synovial fluid examination the viscosity test as well as measurement of other parameters (e.g. pH, special gravity, turbidity etc) was not always performed due to the limited sample size. In general, the synovial fluid deriving from the right femorotibial joint presented mostly with abnormal colour (varying from medium yellow to bloody with clots) and decreased quantity (1/3 of a “lentil drop” to one drop) compared with the fluid of the left joint (pale yellow with few clots and one to two “lentil drops”). In one case (Bird No 1) the colour of the “right synovial fluid” was normal (pale yellow), while in another the amount of the collected fluid was larger in the right femorotibial joint than in the left joint (Bird No 4) (see also Annex XV). In the microscopic examination, erythrocytes were prevalent in the fluid originating from the right femorotibial joint. No granulocytes (heterophiles, eosinophiles, and basophiles), lymphocytes, monocytes or macrophages were detected. Fluid from the left femorotibial joints had a normal appearance (synoviocytes and few erythrocytes), similar to that of the intact birds.

5.5 Histology

5.5.1 Muscle

In general, the diagnosis of the muscle histology stained with hematoxyline and eosin was slight to mild degeneration and regeneration signs, in different muscle sections, with focal to multi-focal fibrosis. Regeneration processes (centralisation of nuclei) were more evident in, but not exclusive to, the right muscle samples. In the EPG the lesions per muscle and nucleus centralisation were more evident in the right femorotibialis muscle (ranging from grade 2 to 3). In one case (Bird No 5) also the left femorotibialis muscle presented an equal amount of centralised nuclei (grade 3= more than 20 nuclei/ field) as the right one. Inflammation and fibrosis were mostly absent (grade 0-1). The fatty tissue in most samples was characterised as extensive (more than 20 fatty cells) (see also Annex XVI). In the LPG the degree of lesion and of centralisation was again higher in the operated (right) femorotibialis muscle. Additionally, birds No 6 and No 8 presented a high centralisation and lesion prevalence also in the right gastrocnemius muscle samples. Differences between groups were not significant. Fibrosis and inflammation were totally absent in all individuals of this group, whilst fatty tissue was again extensive (see also Annex XVI).

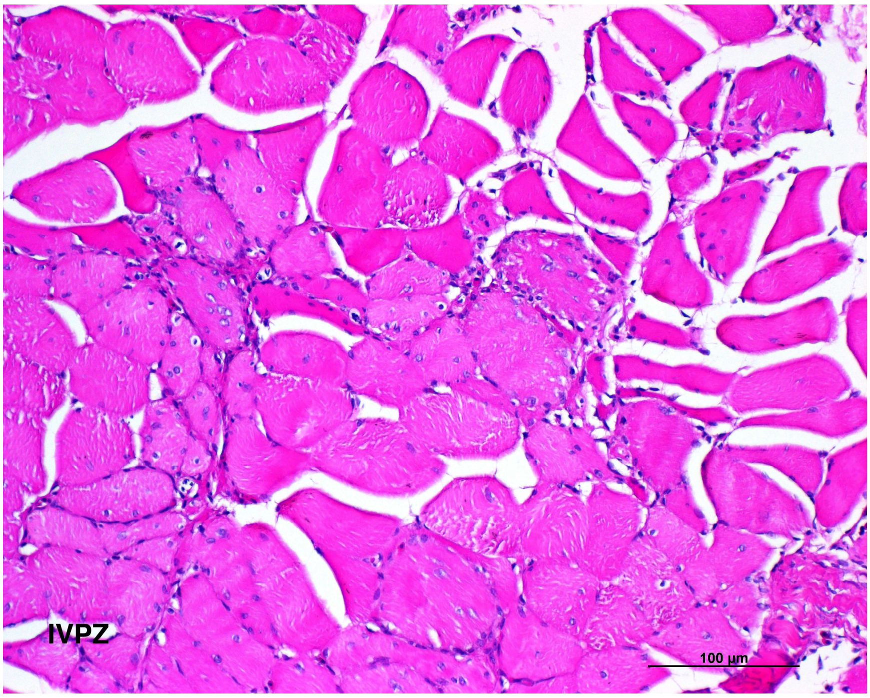


Figure 23: Fiber diameter variation. (Left) normal fiber. (Right) impacted (fibrotic) fibres (Pigeon. Right femorotibialis muscle, H & E stain).

5.5.1.1 Muscle fibre morphometry

The right femorotibialis muscle of both groups of treated pigeons were below the “normal range“, derived from the two intact pigeon (Table 8). On the other hand, one left femorotibial muscle marginally exceeded the normal range, suggesting slight muscle hypertrophy. The left gastrocnemii were within the normal range, which surprisingly differed from the right one.

Table 8: Indicative fibre morphometry in pigeons expressed as mean fibre diameter (in µm)

Muscle	Pigeon 4	Pigeon 7	Normal Range
Right Femorotibialis	49	52	56-68
Left Femorotibialis	62	74	
Right Gastrocnemius	71	89	54-74
Left Gastrocnemius	70	70	

Figure 24: Random muscle morphometry (Pigeon. Right femorotibialis muscle, H & E stain)

5.5.2 Femorotibial joint

The histologic examination for possible ongoing luxation or inaccurate repositioning revealed a possible luxation in five out of eight operated pigeons and one case (Bird No 7) of certain luxation (see Annex XVII), in which the caudal aspect of the femoral condyle was obviously positioned cranially of the cranial tibiotarsal margin. In the remaining suspected cases of luxation the femur was slightly shifted cranially from the tibiotarsal margins or the interosseous gap was broader than considered normal. As expected, there were significantly more cases of suspected luxations in the right than in the left (non-operated) femorotibial joint (p=0.02). No trace of amyloid deposits or inflammation was identified and only two suspected cases of fibrosis (Bird No 2 and 4) were recorded.

The definitive or possible presence of osteophytes was recorded in the right joint in five cases. Two birds of LPG (No 4, 8) presented osteophytes and three more (No 2, 5, 7) of both groups possible osteophytes. These presented as osseous mineralised areas in the cranial or caudal tibiotarsus, exceeding the marginal bone line. The right femorotibial joint had a significantly higher prevalence of osteophytes (p=0.038) than the left. (ANNEX XIX, Fig. 38, 39)

Remodelling of the trabecular bone, represented by the amount of osteoid areas (ANNEX XVIII), was not evident as all of the pigeons scored as normal, with only few areas of newly dep osited osteoid in both the femoral and tibiotarsal trabecular bone. One of the controls (No 9) had a higher score (1 in right joint and 2 in the left). (see ANNEX XIX, Fig. 40)The evaluation of the articular cartilage with the Mankin score, did not reveal significant differences between the two groups. Among all birds, lesions (and subsequently Mankin score) of the femoral central area in the right joint were significantly more pronounced than in the left joint (p= 0.04). Additionally, cartilage lesions in the femoral central area were significantly more pronounced than in the femoral peripheral area prevalent (p= 0.017). In detail, the structural changes observed in the femur central area (left and right) were; irregular surface (N=1/16), pannus and surface irregularities (N= 5/16 samples), cleft to radial zone (N=1/16), and cleft to calcified zone (N=1/16). In the tibiotarsal central area the following lesions were recorded; irregular surface (N=1/16), pannus and irregular surface (N=3/16), cleft to the radial zone (N=3/16) and one with complete disorganization (N=1/16). The peripheral zones (cranial or caudal, femoral or tibiotarsal) showed less severe lesions (expressed as Mankin score), namely; pannus and irregular surface (N=6/32) and cleft to transitional zone (N=1/16) (see also ANNEXES XVII, XIX and Fig. 25, 26, 27).

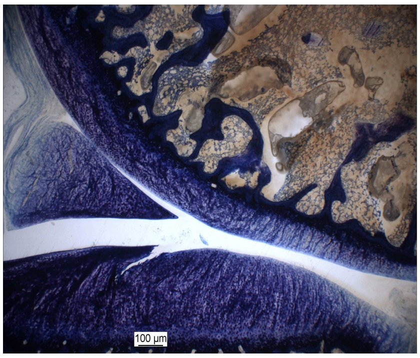


Figure 25: Cleft to transitional zone (tibiotarsus) (thick section, toluidine blue).

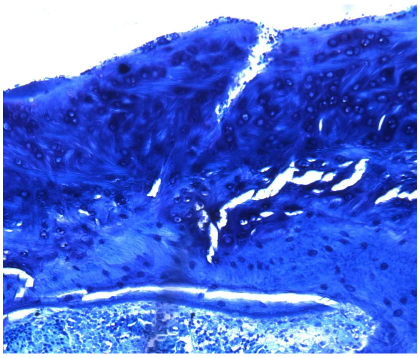


Figure 26: Cleft to radial zone (thin section, toluidine blue).

Figure 27: Cleft to calcified zone (thick section, toluidine blue).

It should be noted that the four samples of the two intact control pigeons revealed lesions and signs of degeneration. Signs of inflammation and osteophytes were recorded in one case (No 10, left limb), cleft to the transitional zone in the right and left femoral central area (No 9) and cleft to the calcified zone in the femoral and tibiotarsal central area (No 10).

6 Discussion

6.1 Critic of the methods

1. Birds were unsexed, because sex variation is not known to affect the orthopedic outcome. Age could not be determined ante-mortem as the birds were wild caught, but only adult pigeons were included in this study. Age-related lesions may have affected the histologic evaluation of the femorotibial joint articular cartilage.

2. Pre-operative measurements, although pre-planned and exercised, took significant time, exposing the birds to prolonged anesthetic risk. To minimize the anesthetic exposure it was assumed that the pre-surgical values of thigh and

ROM measurements would be equal between left and right hindlimb although it would have been better, in hindisght to have values, from both legs to increase the sample and have more representative mean values.

3. The physical therapy trial (and subsequently the produced measurements) was not blinded, since ideally an equally experienced veterinarian, who would not be aware of the bird’s history, should have performed physical therapy. To keep the study as much randon as possible, birds were randomly divided in two groups and a day after day pattern (one with physical therapy, one without) was applied, to avoid as much as possible the normality of the group.

4. Intra-capsular and soft tissue damage, although minimized as possible, might have differed between individuals due to variation in surgical performance. A possible implication to the scores of physiotherapy measurements, muscle histology and joint histology could not be excluded.

5. Variations in the technique application quality, due to progressive familiarisation with it, were inevitable. The total operational time was lower in the later operated individuals. Nevertheless this did not seem to influence the results.

6. Subcutaneous injections located in the groin, resulting in skin necrosis, may have played a role in lameness evaluation. Pain due to skin necrosis could stress the birds, in a way to move unwillingly and not use the respected leg, contributing to the development of pododermatitis, which subsequently could be assessed in the lameness score.

7. For this study the positive effect of physical therapy after orthopedic surgery was taken for granted, because it is stressed in most avian textbooks as well as specific physical therapy publications/reviews. Therefore, it was thought pointless to compare a group without physical therapy with one with physical therapy (early or late), since the outcome was believed to be fairly predictable. After critical review of the literature it was concluded, however, that all recommendations for physical therapy in avian literature used either single cases (rehabilitated wild birds) or extrapolated data from small animal medicine.

An original study that includes with control group without physical therapy, that actually proves the positive effect of physical therapy after orthopedic surgery has not been published so far. Therefore, in hindsight, it would have probably been more valuable to include such a control group rather than to compare different regimes of physical therapy. This is definitely an issue for further research, because if could be assumed that birds recover even without physical therapy, which would save relevant manpower.

8. Sliding of the goniometer or the metric tape could not be avoided, when measuring the angle or the thigh muscle circumference, resulting to slightly inaccurate values. Feathers and skin may have affected the accuracy of the metric tape placement as well. The use of other tools (e.g. pachymeter) could be more accurate with less defeathering needed and should be investigated in the future.

9. Absence of a significant difference between the groups could have been an effect of low sample size, or could indicate that the time point of physical therapy is not critical in this type of lesion and recovery. Due to the fact that all surgeries, physical therapy sessions and measurements were performed by the same investigator to achieve maximum consistency, and were performed as one experiment at a given time to avoid variation due to seasonal differences or differences in investigating personnell, the number of animal investigated actually represented the physical and logistic maximum possible.

10. Accuracy, during the preparation of the joint histologic sample (especially the exact midpoint of the femoral condyles and the intercondylar groove) may have differed slightly between individuals, affecting the quantity of the findings. Additionally, the joint position during embedding (not totally vertical position) may have influenced the interpretation during the histologic evaluation for luxation. In future studies, a more throroughout histologic examination should be performed, consisting of evaluation of more than three slides per joint, in order to quantify the assessment of histologic lesions in detail. Moreover during the embedding process care should be taken to place the joint vertical to the plate bottom.

11. The muscle fibre morphometry could have been applied to more samples, measuring more fibres (Nicks et al. 1989). The “normal range” could have been more reliable if more intact pigeons had been examined. The left gastrocnemius presented identical value between the two examined individual. We consider it as coincidence, since the measured fibre bundles (and the fibres within a bundle) were selected randomly.

12. Non-clinical assessment of muscle atrophy could have also included additional laboratory measurements such as muscle dry weight and water content, fat content, muscle/body mass ratio, muscle and serum lipase activity, as proposed earlier (George and Vallyathan 1962).

6.2 Discussion of the results

6.2.1 Fixation technique and use of FESSA hinged model

The techniques so far described in the literature for stifle luxation management can be distinguished roughly in those which aim to achieve an arthrodesis and those which aim to restore as much as possible of the normal range of motion. Furthermore, it is suggested that a luxation should be reduced as early as possible, since fibrosis and ankylosis can be induced within as little as three days (Bennett 1998). This statement is probably based upon personal observation and experience, since a single citation (on avian medicine) claiming this could not be located. Therefore, it is proposed that the real induction time of fibrosis/ankylosis should be further investigated, as it may vary among species, and this limit should be handled with precaution, with respect to the prognosis and the method of treatment. Additionally, open techniques to reduce a stifle luxation are more preferable than closed techniques, as the latter offer only poor anatomic reduction and stabilization (Behrens et al. 1989). Arthrotomy has been used successfully in birds to achieve access in the femorotibial joint (Jaffe et al. 2000; Alievi et al. 2001; Villaverde et al. 2005; Harris et al. 2007), despite older cases suggesting increased morbidity after exploratory arthrotomy (Bowles and Zantop 2002)

In this study, the proposed technique aimed to achieve the best possible stabilization of the repositioned joint and after physical therapy the best range of motion. Accurate stabilization of the joint is an important factor for luxation healing (Roush 1980). Therefore, the combination of the collateral ligament prosthesis and external stabilization was chosen, despite the fact that all previous authors have applied solely one technique with a satisfying clinical functional outcome, which was defined as the ability of the bird to use its limb for percing, standing or gaiting.

The decision to thread the suture through the fibular head instead through the cranial cnemial crest was made after studying the literature and the anatomy of the joint. It is thought that the fibular head is a well-recognised landmark in most of the common species seen in the praxis, easily accessed with the lateral approach, as it lies in the same vertical course as the lateral collateral ligament. Presumably, this can help to achieve an accurate bone reposition and moreover reduce the tension in the suture. This tension might be increased if the cranial cnemial technique was chosen, since this structure is located more cranially than the fibular head. The faster option to pass the band under the fibular head as proposed by a previous study (Villaverde et al. 2005) was rejected due to the possible increased risk to stress the tibiofibular syndesmosis, resulting to the gradual tearing of the *Lig. tibiofibulare* obliquum and/or *Lig. tibiofibulare craniale*, due to the intense physical therapy. The “figure of eight” suture band was supposed to facilitate the reconstitution of the collateral ligament, which is important to restore joint alignment (Keller et al. 1994), while the transarticular ESF stabilizes the bones, prohibiting rotational and weight-bearing forces. As in lateral collateral ligament injuries the ligament should be sutured in extension, to avoid shortening, which could limit extension or overstress the repair (Piermattei et al. 2006), therefore in this study the band was fixed in a medium position, permitting some laxity but not rotation. Rosenthal et al. (1994) mention that a significant disadvantage of the tension band and the bone screw technique is the inability to readjust the angle after the screw is placed. In contrast, in this study it was possible to readjust the angle from 60^{o} to 70^{o} after ten days by readjusting the hinge of the HLESF. Moreover, the band was fixed with the joint in some extension, and the nylon suture also possesses some elasticity. Two facts led to the decision to readjust the angle; the discomfort of some of the birds to bear weight and the incertainty about the accurate normal standing angle in the pigeon. Discomfort after ESF application is expected, as it has been also addressed in another study (Clipsham 1991b). In the case of this other study, the discomfort dissolved after five days, whilst in the present study discomfort was detectable after seven days postoperatively despite the use of analgesics. The goniometric measurements of this study in anesthetised and dead pigeons, as well as from previous studies (Thompson and Bassett 1970; Villaverde et al. 2005; Bonin et al. 2007; Harris et al. 2007) indicate that the normal angle is 60^{o}, although a fundamental anatomic study of the pigeon hind limb by Cracraft (1971) suggested that the normal standing angle is around 90^{o}. According to our clinical observations, a medium value of the angle ($70\text{-}75^{o}$) could also allow the birds to perform their basic limb movements. This fact suggests that the hypothesis of Cracraft (1971) is probably not accurate, while the last 30 years more reliable methods have also been developed. After the readjustment of the angle most birds showed faster recovery in terms of weight bearing on the operated limb. Moreover, it was earlier proposed that external skeletal fixators if permitted 5^{o}-10^{o} of joint motion, would benefit the articular cartilage restoration (Behrens et al. 1989). This fact highlights the need of more accurate studies for the normal standing angles in different avian species.

External skeletal fixation proved useful to stabilize the stifle joint or to achieve arthrodesis. Transarticular ESF as applied in small animal medicine has been proposed to have provided a more stable configuration for a Solomon Island Eclectus parrot *(Eclectus roratus solomonensis)* with a stifle luxation (Harris et al. 2007). According to Keller et al. (1994) transarticular ESF offered reliable immobilization, selective immobilization of a single joint leaving the other joints (coxofemoral and tarsometatarsal) free to move, access to the immobilized limb for soft-tissue care and angle readjustment to enhance weight bearing minimizing disuse atrophy and excessive loading of the uninvolved limb. The transarticular ESF lacks the disadvantages of the intramedullary pinning and transfixation pins, where the pin could interfere with the normal stifle function, if inserted in the articular cavity (MacCoy 1986) and could become a source of osteomyelitis. More recently, Harris et al (2007) treated a Solomon Island Eclectus parrot for osteomyelitis after the stabilization of the stifle joint with two conjoined intramedullary pins. Osteophytosis, suggestive of chronic instability, along the periarticular margins of the stifle was detectable sixty-nine days postoperatively (Harris et al. 2007). On the other hand, intramedullary pin allows limb growth in paediatric patients and is easier and quicker to apply (Bowles and Zantop 2002). Disadvantages of ESF include pathologic fractures, increased anesthetic and surgical duration, increased weight of the fixator affecting negatively the recovery duration and increased risk of pin loosening (Harcourt-Brown 2000; Bowles and Zantop 2002). Regarding anesthetic and surgical time this is not reported in previous case reports, which used intramedullary pining or external fixation (Rosenthal et al. 1994; Donato 2000; Jaffe et al. 2000; Alievi et al. 2001; Bowles and Zantop 2002; Villaverde et al. 2005; Harris et al. 2007), while Villaverde et al (2005) commented that decreased anesthetic/surgical time was observed only if the luxation was managed by external coaptation or single tension band. In the current study, the anesthetic time cannot be used to simulate the practice conditions, since it was prolonged due to the physical therapeutical measurements. Though, the mean surgical time was considered acceptable for a double orthopedic procedure, taking also in account that the duration of the last surgical procedure was only ninety-five minutes.

FESSA is leight-weighted (the hinge, tubes and screws weighted 10 grams), system, providing placement accuracy, rigidity, stability of pins and configuration and gradual dynamization. Moreover, the hinge allows early mobilization of the joint, without requiring the removal of the ESF, an option that other ESF models cannot offer. That advantage was used to provide early postoperative physical therapy to one of the two bird groups. Although pin loosening was reported in previous studies with FESSA (Hatt et al. 2007) it was not significant (one case in 32 pins) in the current study and did not result in unstable configuration. Pin loosening and unstable configuration are highly dependent from the number and type of pins used as well as the insertion technique. Some studies (Clipsham 1991a; Donato 2000; Hatt and Sandmeier 2003; Hatt et al. 2007) proposed that three pins per bone would be ideal to achieve increased stability; in this study satisfactory stability was achieved with only two positive-threaded pins per bone. The size of the species used for this study and the type of the configuration could not allow a third pin to be placed safely. Moreover, Hatt et al (2007) have used negative profile pins, which generally carry greater risk of sliding, in contrast with this study where only positive profile mini pins were used. According to (Palmer et al. 1991) the prevalence of pin loosening may be lowered if positive-profile pins are used, since they possess better pin-bone interface stability than Ellis pins (Degernes et al. 1998). For additional safety and stability one tibiotarsal pin was always placed in 40-45^o angle.

Stabilization of the joint and that of the HLESF were evaluated daily, through orthopedic and macroscopic examination, as well as histologically after six weeks. No drawer movement or rotation was detected. At post mortem examination of the operated joint, caseous fibrotic material was present. This finding had been expected, because scar stabilising tissue in the joint develops within 3-6 weeks (Bennett 1998). The migration of the bone screw in one case did not seem to compromise the overall stability of the joint in the particular case.

It is interesting to note the formation of excessive callus in the pin insertion sites which may be attributed to periosteal reaction. No bony changes or complications were observed radiographically between the groups complying with the results of former studies (Villaverde et al. 2005); Monk et al 2006). Muscle histology revealed the damage caused due to pin insertion and shear/friction forces during the early physiotherapy. This was more prominent to the right femorotibialis muscle. This damage, according to the specialist pathologist, was evaluated as non-significant for the future limb and muscle function as regeneration of the muscle fibres was in progress and the fibrotic areas were isolated. The latter confirms the statement that ESF causes minimal trauma to soft-tissues and osseous vascularity, if properly applied (Toombs 1992; Hernadez-Divers et al. 2007).

The femorotibial joint histology suggested high prevalence of possible luxation (ANNEX XIX, Figure 25, 26, 27), despite the fact that clinically no motion was observed and the postoperative radiographs showed optimal bone alignment. Moreover, calcifications and possible presence of osteophytes indicate instability also with this double surgical technique. Periarticular new bone formation (ANNEX XX, Figure 33) has been attributed to trauma to the joint capsule as well (Hulse and Shires 1986; Bruce 1998). In man and birds, peripheral remodelling and marginal osteophyte formation are not necessarily related to destructive joint changes (Duff 1987b). Recently, it was reported that trabecular bone in the avian femorotibial joint is highly sensitive to changes in load orientation. Remodelling of the subchondral and trabecular bone, represented by osteoid production (dyed turquoise with the van

Kossa/McNeal stain) from the immature bone, is the indicator of bone activity. If the bone is inactive with diminished osteogenesis, osteoid is absent or isolated, while in cases of intense bone activity (e.g. osteoarthritis), osteoid appears abundant in the inner side of the trabeculae (Fiechter 2005). According to Mankin et al (1971) 0-10 osteoid areas/field represent restricted bone activity, 11-20 areas mild activity and more than 20 areas/field high activity. In birds a similar scale has not been described, and therefore a modified version using lower values was applied. Though, in future studies it is proposed that a more species- specific scale should be elaborated.
The importance of these findings is, that probably the bone reposition and joint stability, when clinically evaluated, is not always reliable. The significance of joint stability is important for joint healing and would even play a more important role in geriatric patients or long-lived species, since they more easily develop osteoarthritis with further compromise of the joint.

6.2.2 Physical therapy effect

Physical therapy was performed under isoflurane general anesthesia. The repeated anaesthesia did not seem to have an impact on the overall health of the birds, although liver and kidneys have been histologically assessed post mortem. Each session lasted about thirty minutes. The HLESF-FESSA proved extremely helpful to perform physical therapy with only minor effort. Really crucial, in terms of mechanics, is the saw-like periphery of the hinge, which some times and if not properly unlocked, could block the motion. This way excessive forces could be transferred to the FESSA, the pins and the articular surfaces, resulting in articular cartilage injury, pin loosening or unstable configuration. A simple proposal to reduce the friction forces between the two hinge hemispheres is the application of a lubricant substance (for instance one ml vaseline) between the hemispheres before each session. To overcome this problem completely, a modified version of the hinge could be developed adding to its medial side a locknut, which could control the extension of the Allen screw during unlocking. Furthermore, during the postoperative period a spring of a specific range of elasticity could be adjusted between the FESSA tubes to allow the patient to self-regulate the range of motion.

Lameness, in this study, resolved throughout the sixth-week period as showed in an earlier, similar study in dogs (Monk et al. 2006), but without significant variance between the two groups. Despite the fact that there are major differences in the anatomy and gait between mammals (dog) and birds, these findings are also similar to a study which used transarticular stifle ESF (Keller et al. 1994) and early physiotherapy after cranial cruciate ligament deficiency, treated with TPLO (Monk et al. 2006). In birds, according to Maccoy (1986), evidence of the return to normal function is the ability to bear weight to the involved limb, to ambulate and balance on the non-affected limb. In a monk parakeet (*Myiopsita monachus*) full return to normal function, after IM pinning, occurred 35 days postsurgically (Bowles and Zantop 2002).

Pododermatitis and perch use were not significantly different between the EPG and LPG. Here, it should be noted that although pigeons are not as susceptible to bumblefoot as other avian families, a specific grading scale should be developed to achieve a more accurate approach. Bruising, increased tension and swelling of the foot pads, exfoliating dermatitis and metatarsal pressure wounds were observed and could contribute towards the development of a more detailed scale, parallel to a long term monitoring to define the advanced stages of the disease in Columbiformes.

With respect to the examination of ROM data it should be taken into consideration that as flexion ROM of the femorotibial joint improves, the angle is reduced; hence, an improvement in flexion is seen as a smaller value. As extension ROM of the stifle improves, the angle becomes larger and improvement in ROM is seen as larger value. The expectation of this study was that the EPG would gain more ROM, even as early as the third week, as this has been reported in an earlier mammalian study (Monk et al. 2006). This was not evident in three weeks but after six weeks a numerical difference between third and sixth week measurement, but statistically non significant, was detectable in the EPG. On the other hand this result matches with the findings of Keller et al (1994). Their experiment included three groups of dogs with transarticular ESF divided in immobilization (control group), immobilization followed by remobilization (group R) and finally immobilization followed by remobilization combined with hyaluronic acid therapy (group RHA). No differences were detected between R and RHA groups for mean ROM as well as lameness score. Moreover, previous reports in avian patients with femorotibial joint luxation and various surgical techniques described a satisfying functional outcome despite loss of ROM (Holz 1992; Rosenthal et al. 1994; Donato 2000; Bowles and Zantop 2002; Fukui 2005; Villaverde et al. 2005). This would be probably explained in respect to the broad range of functional angles in perching birds. For example, the pigeon uses mostly a flexion-extension range between 38^o-144^o for walking, standing and running (Cracraft 1971), so even after 40^o loss of extension ROM the pigeons could ambulate, perch, walk, stand or try to copulate and fight. On the contrary, in dogs this range lies between 28^o-172^o (Mann et al. 1988a; Jaegger et al. 2002a) being possibly more gravely influenced by loss in ROM.

Thigh circumference (TC) measurement is proposed in human and small animal medicine to provide an indication of muscle atrophy, as it is inexpensive, simple to measure and does not require sedation or general anesthesia (Levine et al. 2005; Monk et al. 2006; Knap et al. 2007). Atrophy of thigh muscles in the biped human after CCL surgery results in delayed return to function and ongoing pain (Shelbourne and Nitz 1990). Prevention of muscle atrophy and restoration of muscle strength are essential for restoring the knee to normal function and preventing reinjury (O'Meara 1993). In birds, TC as well as ROM measurements could not be performed without general anesthesia. In the present study TC did not provide satisfactory data, being influenced by the feathers and the abdominal wall. All measurements were accomplished mostly in the lower third of the thigh muscle, as the middle-thigh was not accessible. On the other hand TTh showed a significance difference between left and right thigh musculature, suggesting possible compensatory hypertrophy of the left limb (presumably as the result of increased workload) with accompanied atrophy of the right. The latter suspicion is additionally supported by the muscle fibre morphometry, in which the right femorotibialis muscle in two pigeons (one of each group) was below the normal range indicating atrophy. However, to accurately assess atrophy, histochemistry should have been performed. Currently, histochemistry is feasible only for mammalian 2A fibres (atrophy affects mostly 2A and 2B fibres), but has not worked for avian 2A fibres, due to lack of proper reactors. Moreover, in mammals, fiber hypertrophy is definitely established if the fiber diameter exceeds the 100 µm (normal 60-70µm). Nevertheless, both measurements (TC and TTh) decreased till the sixth week following the same pattern in both limbs, leading to the assumption that probably early physiotherapy did not increase the endurance and weight of the thigh musculature and subsequently the thigh thickness. If the monitoring would continue for longer period these results might have been more striking and destructive for the muscle viable function.

In this study we investigated also the impact of surgery and physical therapy on cartilage and intra-articular structures. It has been frequently reported in mammals that restricting the movement of diarthroidal joints is known to have a number of deleterious effects on the articular cartilage (Evans et al. 1960; Roy 1970; Thompson and Bassett 1970; Sood 1971; Akeson et al. 1973; Troyer 1975; Jurvelin et al. 1986; Jurvelin et al. 1989). The cartilage becomes softer and therefore less resilient, and loss of matrix proteoglycan is induced by immobilization (Jurvelin et al. 1986; Jurvelin et al. 1989). The softened cartilage may be unable to counter balance the weight-bearing forces and become damaged (Jurvelin et al. 1989). Transarticular ESF may induce a greater loss of proteoglycan (Keller et al. 1994) as the one induced by simple external coaptation, due to the greater degree of immobilization (Behrens et al. 1989). It is reported that proteoglycan metabolism in the avian articular cartilage during the development of DJD is similar to the mammalian (Venkatesan et al. 1999). Cartilage stiffness and resiliency can be regained, after remobilization, but not in full extend following even a 50- week remobilization period (Jurvelin et al. 1989; Haapala et al. 1999). In the current study, lesions in the articular cartilage of the right femorotibial joint were more significant than the left. This result was predicted since the right limb was operated, but it is also reported that immobilisation causes long-lasting matrix changes both in the immobilised and the contralateral joint cartilage in the human (Jortikka et al. 1997). Though, according to Roush et al. (1989), non-immobilized rabbit stifles had better histologic quality, represented by increased safranin stain uptake and more normal collagen fiber orientation at sixty days than stifles immobilized for seven to fourteen days. Additionally, the peripheral cartilage areas in the pigeons were less severely affected than the opposed central cartilage areas. This was expected, as the central part of the joint cartilage participates more in the joint motion and receives the main pressure and rotation forces. Nevertheless, all areas were affected as reported in a previous study in dogs (Behrens et al. 1989). Only little information could be found in the literature regarding the type of lesions in the articular cartilage after joint remobilization. In a study in which three groups of dogs were immobilized with a trans-stifle ESF and received remobilization for four weeks after ESF removal, the following lesions, in the remobilized group, were described: disrupted surface, disorientation of tangential zone matrix fibres, loss of chondrocytes from tangential and outer intermediate zones and less alcian blue staining (Keller et al. 1994). Another study in rabbits (Thompson and Bassett 1970) revealed that after four weeks of compression, the periphery of the compressed zones showed chondrocyte cloning and changes in orientation of the collagen architecture**,** but not gross vascular invasion of the zone of calcified cartilage. The centre of the compressed area demonstrated a gradual decrease in thickness of the articular cartilage and marked changes in orientation of the collagen bundles.

Although the present study did not included proteoglycan, cartilage thickness and collagen fibre evaluation, it is clear that the prevalent structural changes as well as in less extend the loss of tolouidine staining suggest that physical therapy (early or late) had an important negative impact to the viability of the intraarticular components of the femorotibial joint. Of course it cannot be excluded that some of these lesions could have been created after iatrogenic induced trauma during surgery or by the self-mobility of the joint by the pigeons, despite the precautions taken. The only other experimental study for avian stifle luxation management has also detected histologic changes in the groups, which were treated with invasive surgical techniques (IM pins and ESF) (Villaverde et al. 2005). Again no significant clinical differences were recorded among the various groups, in terms of periarticular fibrosis and bone reaction, while the study lacks of concrete details of the evaluation protocol and the specific findings. The former indications of extensive intraarticular damage should be further investigated, but also seriously considered under clinical circumstances, prior of the management. These indications may also justify why almost all described surgical techniques to resolve a femorotibial luxation, are ranked as successful. An arthrodesis (although unwanted) may seem inevitable and so there is not a marked healing difference between surgical techniques, which aim to induce complete arthrodesis and those which aim just to support the joint in order to reduce the loss of ROM.

6.3 Application flexibility of the methods in the ordinary clinical practise

The presented technique to stabilise a femorotibial joint luxation can be easily adapted for avian veterinary practice.

Except for the FESSA materials, no other material was used that cannot be found in an average small animal practise. Despite the fact that the cost of the system used in this study appears high (91 CHF/ 87.30 USD/ 56.12 EURO) especially if we add the cost of the pins and the cortical screw, this can be lowered as FESSA is re-sterilisable and therefore re-usable. The familiarisation with the FESSA application is easy, as it follows the general external fixation principles. Special attention should be given to fragility of avian bones (Bennett and Kuzma 1992) during the insertion of ESF pins and therefore proper size and type of pins (e.g. mini positive threaded, use of pencil hand chuck) is regarded as important element of the successful application. In more detail, for the hinged FESSA, the choice of the proper Instant Center of Rotation (ICR) is also considered elementary for the function of the hinge for joint management. For the routine practice, this could be roughly assumed as the geometric centre of the joint, but always with an intra-operative motility check. Experienced avian veterinarians or small animal surgeons could easily perform the technique.

The two different bar and hinge diameters (6mm and 8mm), as well as the variable FESSA tube length, facilitate its use from middle-sized cage avian species to larger raptor and wading species. Apart from the fixation of the femorotibial joint, as demonstrated in this study, it could also be applied under the same principles to the elbow luxations (as shown in Fig. 28). A further possible application could be the ratite toe fixation (after dislocation or periarticular fracture). In this case, the permanently loosened hinge could serve as self-exercising mechanism, allowing for some joint mobilization.

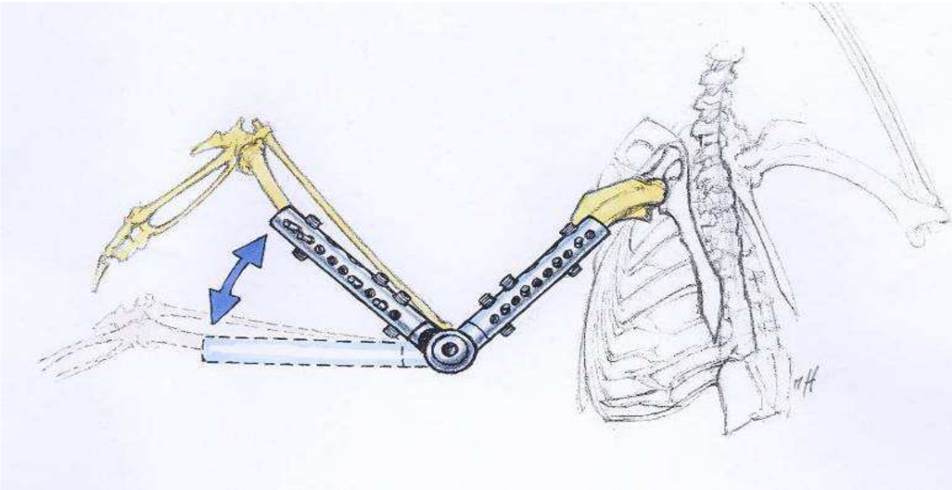


Figure 28: Proposed application of the FESSA-Hinged Linear External Skeletal Fixator (HLESF) in the avian elbow joint, for management of luxation or periarticular fracture. The arrow indicates the proposed direction of motion during physiotherapy. The hinge should be applied on the dorsal aspect of the elbow, to allow inspection and proper motion control (Drawing by M. Haab)

Additionally, the special plan of physical therapy developed for this study could be easily applied to birds with femorotibial joint luxation in the practice, the rehabilitation facility or in home by instructing the owner. It could also serve as the base of a more complex plan, using additional physical therapy modalities (as cryotherapy, ultrasound, weight-shifting exercises, foam pad etc), after a controlled study will show the benefit of physical therapy. Otherwise, the positive effect of physical therapy should not be taken as granted. To monitor the development of the patient the Thigh Thickness (or the biceps/triceps in the case of the pectoral limb) could be measured in both limbs with the help of metal, rigid, French-key type meter, under appropriate manual restraint, sedation or isoflurane anesthesia.

7 Conclusions

The main conclusions from this study are summarized below.

1. An extensive literature survey revealed lack of original and experimental studies not only for the avian femorotibial joint luxation, but in general for all types of avian luxations. Most data and knowledge on luxation aetiology, prevalence and management is derived from published case reports, anecdotal personal experience or extrapolation from small animal medicine. An attempt to give an overview was made earlier (Bennett 1998), but should be updated since new knowledge has been produced. A more recent experimental effort (Villaverde et al. 2005) on femorotibial joint luxation produced interesting preliminary results, but unfortunately was never published in full extend, leaving many gaps for the methods and the complete results.
2. The anatomy of the avian femorotibial joint is complex and differs from the mammalian in many anatomic and functional aspects. Based on the publications retrieved for the purposes of the present study, it is concluded that little intra- and inter-specific variation should be expected. In terms of function, there are crucial differences among the species reviewed, especially with respect to the range of the normal functional angles and their behaviour (ground dwelling, hopping, perching, aerial or intermediate gait species). In that direction further species-specific research would be beneficial and with clinical application. A first effort to evaluate the normal perching angles in different non-sedated avian species has been recently taken (Bonin et al. 2007).
3. According to the literature, the reduction of a femorotibial joint luxation can be achieved with more than ten surgical techniques, which are all reported to produce a satisfactory functional outcome. This fact provides the avian clinicians with more flexibility to choose the technique according to the individual case, since all of them share advantages and disadvantages. Though further comparative experimental studies should be launched in order to accurately assess, clinically and especially microscopically, the impact and benefit of each technique.

4. The current study tested the FESSA hinged model as a Hinged Linear External Skeletal Fixator (HLESF), in combination with the extracapsular collateral ligament prosthesis, for the management of stifle luxation in pigeons. It is concluded that the use of HLESF in avian luxations is as advantageous as its use in mammalian luxations, providing rigid stabilization and possibility of early remobilization through physical therapy. Moreover, it could speed healing allowing the patient to self-regulate the acceptable range of motion during the later postoperative period. Although in small animal surgery there are different options to create a HLESF, in avian surgery the FESSA has proved to be of great value. Already positively tested in avian fracture management, in the configuration of HLESF, FESSA provided joint stability, rigidity, minimal complications and comfort to the avian patient due to its leight weight. Partially, the positive surgical outcome should be ascribed to the ligament prosthesis as well as to the combination of ligament prosthesis and HLESF, which concentrated the advantages of both techniques. The extend to which each component contributed to the success of the procedure could be further surveyed in the context of the broader comparative study of the various surgical techniques.
5. Beyond the surgical combination, the present study intended to evaluate for the first time the positive effect and importance of early postoperative physical therapy after stifle surgery, as this was stressed in other small animal studies. Although our expectations, driven by the avian and mammalian literature, pointed towards a definite positive effect, this was not corroborated. There was no significant, gross difference in the evaluated clinical and histologic parameters between the two examined groups, suggesting that immediate postoperative physiotherapy (one to two days after surgery) has limited value in accelerating and improving the healing process. Alternative methods to speed healing should be investigated. For instance, in humans the preoperative administration of the anxiolytic gabapentin has improved femorotibial joint remobilization through preoperative anxiolysis and postoperative analgesia (Menigaux et al. 2005). Though, pharmacokinetic studies focused on birds should be further developed before its broader use.
6. Monitoring of the effect of physical therapy in avian patients is more effective with the ROM, as in mammals, and the Thigh Thickness. The measurement of

the Thigh Circumference (as used in small animal medicine) proved problematic, due to the avian anatomy, producing questionable data.

7. After critical review of the available literature on avian rehabilitation and taking into consideration the neutral results of the early physical therapy, it was found that the widely accepted positive effect of physical therapy in birds, is based on limited clinical case studies and logical extrapolation from human and mammalian medicine and not in controlled experiments. Therefore it would be crucial to conduct a future study focused on the effect of physical therapy in birds with physical therapy versus birds without physical therapy, especially with respect to the additional workload and manpower required for physical therapy.
8. Histology was important to evaluate the impact of the HLESF, the muscle atrophy and the intra- articular impalement. The pin insertion, as expected, affected the structure of the large pelvic muscle groups, but in a reversible manner. Muscle atrophy was indicated for the right femorotibialis muscle. Finally, destruction of articular cartilage, although not exclusively, was more prominent to the treated and most intensively exercised limb. Central area cartilage was more affected. An interesting future research could deal with the cartilage-protective use of hyaluronic acid, as proposed in small mammals.

8 Bibliography

Abourachid A (1993) Mechanics of standing in birds: Functional explanation of lameness problems in giant turkeys. Br Poul Sci 34:887-898

Abourachid A (2001) Kinematic parameters of terestrial locomotion in cursorial (ratites), swimming (ducks), and striding birds (quail and guinea fowl). Comp Biochem Physiol 131:113-119

Abourachid A, Renous S (2000) Bipedal locomotion in ratites (Paleognatiform): examples of cursorial birds. Ibis 142:538-549

Ackermann J, Redig P (1997) Surgical repair of elbow luxation in raptors. J Avian Med Surg 11:247-254

Akeson W, Woo S, Amiel D, et al (1973) The connective tissue response to immobility: Biochemical changes in periarticular connective tissue of the immobilized rabbit knee. Clin Orthop 93:356-362

Alexander RM (2004) Bipedal animals and their differences from humans. J Anat 204:321-330

Alievi M, Hippler R, Giacomelli L, Guimarães L, Schossler J (2001) External Skeletal Fixation for arthrodesis of the knee joint in a parrot (*Amazona aestiva*). Cienc Rural 31:1069-1072

Altman R (1982) Disorders of the skeletal system. In: Petrak M (ed) Diseases of cage and aviary birds, 2nd edn. Lea & Febiger, Philadelphia, pp 141-142

Amiel D, Abel M, Kleiner J, al. e (1986) Synovial fluid nutrient delivery in the diarthroidal joint: An analysis of rabbit knee ligaments. J Orthop Res 4:90-95

Anderson I (1991) Fracture disease and related contractures. In: Olmstead L (ed) Vet Clin North Am Small Anim Pract 21: 845-858

Arnoczky S (1988) The cruciate ligaments: the enigma of the canine stifle. J Small Anim Pract 29:71-90

Baumel J (1993) Systema Cardiovasculare. In: Baumel J (ed) Handbook of Avian Anatomy: Nomina Anatomica Avium, 2nd edn. Nutthall Ornithological Club, Cambridge, MA, USA, pp 407-476

Baumel J, Raikow J (1993) Arthrologia. In: Baumel J (ed) Handbook of Avian Anatomy: Nomina Anatomica Avium, 2nd edn. Nuttall Ornithological Club, Cambridge,MA, USA, pp 133-187

Baumel JJ (1978) Handbook of Avian Anatomy: Nomina Anatomica Avium, 1st edn. Nutthall Ornithological Club

Behrens F, Kraft E, Oegema T (1989) Biochemical changes in articular cartilage after joint immobilization by casting or external fixation. J Orthop Res 7:335-343

Benjamin M (1999) An introduction to synovial joints. In: Archer W, Caterson B, Benjamin M, Ralps J (eds) Biology of synovial joints. Hardwood Academic Publishers, pp 1-10

Bennett R (1993) Instrumentation, preparation, and suture materials for avian surgery. Semin Avian Exot Pet Med 2:62-68

Bennett R (1997) Orthopedic Surgery. In: Altman B, Clubb L, Dorrestein M, Quesenberry K (eds) Avian Medicine and Surgery, 1st edn. SAUNDERS, Philadelphia, Pennsylvania, USA, p 733

Bennett R (1998) Management of joint luxations in birds. In: Reynolds M (ed) "From Science to Reality: A Bridge to the 21st Century". Proc Int Wild Rehabil Counc (IWRC) Concorde, California, pp 11-15

Bennett R, Kuzma B (1992) Fracture management in birds. J Zoo Wild Med 23:5-38

Bonin G, Lauer SK, Tully TN et al. (2007) Radiographic evaluation of perching joint angles in avian species. In: Proc 9th Conf Eur Assoc Avian Vet, 7th ECAMS Scientific Meeting Zürich, Switzerland, pp 288-292

Boskey A (1981) Current concepts on the physiology and biochemistry of calcification. Clin Orthop 167:225-257

Boulet T (2005) Reconstruction du ligament tibio-rotulien. Point-Veterinaire (France) 253:58-61

Bowles H, Zantop D (2002) A novel surgical technique for luxation repair of the femorotibial joint in a monk parakeet (*Myiopsitta monachus*). J Avian Med Surg 16:34-38
Bruce W (1998) Multiple ligamentous injuries of the canine stifle joint: a study of 12 cases. J Small Anim Pract 39:333-340
Bush M (1977) External fixation of avian fractures. J Am Vet Med Assoc 171:943-946
Campbell T (1987) Excision arthroplasty in a Toco toucan (*Ramphastos toco toco*) for the correction of an osteoarthritis of the right coxofemoral joint. In: Proc First Int Conf Zool Avian Med, pp 277-278
Campbell T, Ellis K (2007) Avian and Exotic Animal Hematology and Cytology. 3rd edn. Blackwell Publishing Ltd, Ames, Iowa, USA
Caron P (1996) Chapter 4: Neurogenic factors in joint pain and disease pathogenesis. In: McIlwraith CW, Trotter WG (eds) Joint Disease in the Horse. W.B. Saunders Company, Philadelphia, PE, USA, pp 70-79
Carpenter D, Cooper R (2000a) Mini review of canine stifle joint anatomy. Anat Histol Embryol 29:321-329
Carpenter D, Cooper R (2000b) Mini review of canine stifle joint anatomy. Anat Histol Embryol 29:321-329
Carpenter J (2003) Cranes. In: Fowler ME, Miller E (eds) Zoo and Wild Animal Medicine, 5th edn. W.B. Saunders co, Philadelphia, Pennsylvania
Chancrin J-L (1994) Utilisation du fixateur externe du service de Santé des Armées en orthopédique vétérinaire. In: Vétérinaires SM (ed). Covely, Genay
Chancrin J-L (1997) FESSA. In: Manuel de fixation externe, Pratique médicale et chirurgicale de l'animal de compagnie, Paris, pp 325-344
Chancrin J-L (2000) Application du FESSA aux rayons superrieurs In: Document d'enseignement du CES de Traumatologie Osteo-Articulaire et Orhopedie Animales. Ecole Nationale Veterinaire, Toulouse
Chancrin J-L, Boubee T, Marguin M (1990) Utilisation du fixateur externe du service de santé des armeés (FESSA) en chirurgie orthopédique vétérinaire: a propos de 29 cas. Pratiq Méd Chir Anim Comp 217-223
Chaplin B (1989) Guidelines for exercise in rehabilitated raptors. Wild J 12:17-20
Chaplin B, Mueller L, Degernes AL (1993) Physiological assessment of rehabilitated raptors prior to release In: Redig P, Cooper J, Remple J, Hunter D (eds) Raptor Biomedicine. University of Minnesota Press, Mineapolis, MI, USA, pp 167-173
Chatre J-L (2003) Bovine Orthopaedics.Two cases of canon bone fractures in calves treated with FESSA. Point-Veterinaire (France) 241:70-72
Chinnadurai S, Spodnick G, Degernes L, DeVoe R, Marcellin-Little D (2009) Use of extracapsular stabilization technique to repair cruciate ligament ruptures in two avian species. J Avian Med Surg 23:307-313
Cho P, Brown R, Anderson M (1984) Comparative gross anatomy of ratites. Zoo Biol 3:133-144
Clipsham R (1991a) Correction of pediatric leg disorders. In: Proc Annu Conf Assoc Avian Vet, pp 200-204
Clipsham R (1991b) Introduction to psittacine pediatrics. Vet Clin North Am Small Anim Pract 21:1361-1391
Coles B (1997) Avian Medicine and Surgery, 2nd edn. Blackwell Science Ltd, Oxford
Comerford J (2006) The stifle joint. In: Barr J, Kirberger M (eds) BSAVA Manual of Canine and Feline Musculoskeletal Imaging. Brittish Small Animal Veterinary Association, Gloucester, UK, pp 135-149
Cooney J, Mueller L (1994) Postoperative management of the avian orthopedic patient Semin Avian Exot Pet Med 3:100-107
Corr S, Maxwell M, Gentle M, Bennett D (2003) Preliminary study of joint disease in poultry by the analysis of synovial fluid. Vet Rec152: 549-554
Corr S, McCorquadale C, Gentle M (1998) Gait analysis of poultry. Res Vet Sci 65:233-238
Crabill R, Honnas M (1996) Surgical condition of ratites. In: Tully T, Shane M (eds) Ratite management, medicine and surgery. Krieger Publishing Company, Malabar, FL, USA, pp 95-103

Cracraft J (1971) The functional morphology of the hind limb of the domestic pigeon, *Columba livia*. Bull Am Mus Nat Hist 144:171-268
David T (1976) Knee-joint prosthesis in a buzzard (*Buteo buteo*). Tierarztl Prax 4:387-389
Davidson R, Kerwin C, Millis L (2005) Rehabilitation for the orthopedic patient. In: Levine D, Millis L, Marcellin-Little J, Taylor A (eds) Vet Clin North Am Small Anim Pract 35:1357-1387
Degernes A, Lynch S, Shivaprasad H (2007) Degenerative joint disease in captive waterfowl. In: Proc Annu Meet Assoc Avian Vet/Assoc Exot Mam Vet. Assoc Avian Vet, Long Island, USA, pp 99-100
Degernes A, Roe C, Abrahms CJ (1998) Holding power of different pin designs and pin insertion methods in avian cortical bone. Vet Surg 27:301-306
Demirkan I, Kilic E (2003) Correction of the intertarsal joint luxation in a rooster by a polyester fibre suture. Vet Cerrahi Derg 9:59-61
Denny R, Butterworth J (2000) A guide to canine and feline orthopedic surgery, Fourth edn. Blackwell Science Ltd, Osney Mead, Oxford,UK
Dobromylskyj P, Flecknell P, Lascelles B, Livingston A, Taylor P, Waterman-Pearson A (2000) Pain assessment. In: Flecknell P, Waterman-Pearson A (eds) Pain management in Animals. W.B. Saunders, London, pp 63-78
Donato N (2000) Stifle arthrodesis in a military Macaw. Utilising safe, hazardous and danger zones. In: Veterinarians AoA (ed) Proc Annu Conf Assoc Avian Vet, pp 121-126
Doty A (1979) Canvasback duck recovers from compound luxation to the wing. Prairie Naturalist 3:89-90
Dubbeldam L (1993) Systema nervosum periphericum. In: Baumel J (ed) Handbook of avian anatomy: Nomina Anatomica Avium, 2nd edn. Nutthall Ornithological Club, Cambridge, MA, USA, pp 555-584
Duff S (1985) Cruciate ligament rupture in young adult broiler knee joints. J Comp Pathol 95:537-547
Duff S (1986a) Further studies on cruciate and collateral knee ligaments in adult broiler fowls. Avian Pathol 15:407-420
Duff S (1986b) Further studies on knee ligament failure in broiler breeding fowls. J Comp Pathol 96:485-491
Duff S (1987a) Meniscal lesions in knee joints of broiler fowls. J Comp Pathol 97:451-462
Duff S (1987b) Thinning of articular cartilage in the domestic fowl. J Comp Pathol 97:41-50
Duff S (1988) Further studies on collateral ligaments of knee and intertarsal joints in domestic fowl. J Comp Pathol 98:461-469
Dye S (1987) An evolutionary perspective of the knee. J Bone Joint Surg 69:976-983
Earls D (2000) Kinematics and mechanics of ground take off in the starling *Sturnus vulgaris* and the quail *Coturnix coturnix*. J Exp Biol 203:725-739
Echols S (2006) Physical therapy as part of orthopedic surgery. In: Edition SA (ed) North American Veterinary Conference, vol. 20, Orlando, FL, USA, pp 1549-1550
Evans C (1992) Response of synovium to mechanical injury. In: Finerman G, Noyes F (eds) Biology and biomechanics of the traumatized synovial joint. American Academy of Orthopedic Surgery, Rosemont, IL, pp 17-26
Evans E, Eggers G, Butler J, al e (1960) Experimental immobilization and remobilization of rat knee joints. J Bone Joint Surg 42:737-758
Fell B (1925) The histogenesis of cartilage and bone in the long bones of embryonic fowl. J Morphol Physiol 40:417-459
Fell B (1934) Experiments on the development in vitro of the avian knee joint. Proc Royal Soc Lond Series B 116:316-351
Ferraz V, Ferrigno C, Isaza R, Pozzi A, Myers D, Atkins A, Wellehan J, Ito K (2010) Treatment of tarsal joint deformities with hinged transarticular external fixators in three young birds. Vet Comp Orthop Traumatol 23:362-365
Fiechter R (2005) Am Schaffmodell reproduziertes Femoroacetabuläres impingement, häufigste Ursache der frühen Osteoarthritis beim nichtdysplastischen Hüftgelenk des Menschen. In: Horse Clinic, vol. Doctoral thesis. Vetsuisse Faculty, Zürich, p 133

Firth MA, Haldane LS (1999) Development of a scale to evaluate postoperative pain in dogs. J Am Vet Med Assoc 214:651-659

Flach EJ, Cooper JE (1991) Clinical and pathological findings in two Mauritian pink pigeons (*Columba mayeri*). Vet Rec 129:48-51

Flammer K, Clubb LS (1994) Neonatology. In: Ritchie WB, Harrison JG, Harrison LR (eds) Avian Medicine: Principles and Application. Wingers, Lake Worth, FL, USA pp 831-836

Foerster SH, Gilson SD, Bennett RA (2000) Surgical correction of palatine bone luxation in a blue-and-gold macaw (*Ara ararauna*). J Avian Med Surg 14:118-121

Fowler ME (1991) Comparative clinical anatomy of ratites. J Zoo Wild Med 22:204-227

Fujita M (2004) Kinematic parameters of the walking of herons, ground-feeders and waterfowl. Comp Biochem Physiol 139:117-124

Fukui D, Bando G, Kosuge M. (2005) Stifle luxation repair by articular stabilization technique with non-absorbable suture in a white-fronted goose and therapeutical trial in a domestic pigeon. Jpn J Zoo Wild Med 10: 49-52

Fuss K (1996) Tibiofibular junction of the South African Ostrich (*Struthio camelus australis*). J Morphol 227:213-226

Fuss K, Gasser R (1992) Cruciate ligaments of the avian knee: Insight into a complex system. J Morphol 214:139-151

Gan B, Huys S, Sherebrin M, Scilley C (1995) The effects of ultrasound treatment on flexor tendon healing in the chicken limb. J Hand Surg 20B: 809-814

Gardner D, McGillivray D (1971) Living articular cartilage is not smooth. Ann Rheum Dis 30:3-9

Gatesy M (1999a) Guineafowl hind limb function. II: Electromyographic analysis and motor pattern evolution. J Morphol 240:127-142

Gatesy M (1999b) Guinefowl hind limb function. I: Cineradiographic analysis and speed effects. J Morphol 240:115-125

Gentle M (1992) Pain in birds. Anim Welf 1:235-247

George C, Vallyathan N (1962) Effect of disuse atrophy on pectoralis muscle and blood in the pigeon. Am J Physiol 202:268-272

Gilsleider E (1994) Ratite orthopedics. Semin Avian Exot Pet Med 3:81-91

Girard G (2003) Le fixateur externe du Service de Santé des Armées (FESSA) chez les carnivores domestiques. Etude rétrospective. In: Ecole National Veterinaire de Lyon, vol. Docteur Veterinaire. Universite Claude-Bernard Lyon I, Lyon, p 166

Gnad D, Jean SG, Homco L, Honnas M (1996) A review of some orthopedic diseases in ostriches, emus and rheas. Agri-Pract 17:28-32

Grimm F (1993) Fracture healing in predatory birds, with specail consideration given to a modified external fixator. In: Redig P, Cooper J, Remple J, Hunter D (eds) Raptor Biomedicine. University of Minessota Press, Minneapolis, pp 136-140

Guillet N (2003) Etudes osteologique des femurs, tibiotarses et tarsometatarses de seizes especes d 'oiseaux marins du littoral atlantique francais. In: Ecole Nationale Veterinaire des Nantes, vol. Doctoral thesis. Univeisité des Nantes, Nantes

Guzman Migallon-Sanchez D, Bubenik J, Lauer SK, Vasanjee S, Mitchell A (2007) Repair of coracoid luxation and a tibiotarsal fracture in a bald eagle. J Avian Med Surg 21:188-195

Haapala J, Arokoski JP, Hyttinen MM et al. (1999) Remobilization does not fully restore immobilization induced articular cartilage atrophy. Clin Orthop Relat Res 362:218-229

Haas B, Reichler I, Montavon P (2003) Use of the tubular external fixator in the treatment of distal radial and ulnar fractures in small dogs and cats. Vet Comp Orthop Traumatol 16:132-137

Haeffner S (1989) Correcting leg and joint abnormalities in long-legged precocial birds, with notes on prevention. In: Ann Meet Am Assoc Zool Parks, pp 563-570

Haines R (1942) The tetrapod knee joint. J Anat 76:270-301

Halata Z, Munger L (1980) The ultrastructure of Ruffini and Herbst corpuscles in the articular capsule of domestic pigeon. Anat Rec 198:681-692

Haltrecht H (2000) Physical therapy. Can Vet J 41:573-574

Hancock A, Stevens J, Biknevicius R (2007) Whole-body mechanics and kinematics of terrestrial locomotion in the Elegant-crested Tinamou (*Eudromia elegans*). Ibis 149:605-614

Harari J (1992) Complications of external skeletal fixation. Vet Clin North Am Small Anim Pract 22:99-107

Harcourt-Brown H (1996) Leg Problems. In: Beynon H, Forbes A, Harcourt-Brown H (eds) BSAVA Manual of Raptors, Pigeons and Waterfowl. Brittish Small Animal Veterinary Association Limited, Cheltenham, Gloucestershire, pp 150-168

Harcourt-Brown H (2000) Anatomy of the pelvic limb In: Harcourt-Brown H (ed) Birds of Prey: Anatomy, Radiology, and Clinical Conditions of the Pelvic Limb. Zoological Education Network, Lake Worth, FL, pp 24-134

Harcourt-Brown H (2002) Orthopedic conditions that affect the avian pelvic limb. Vet Clin North Am Exot Anim Pract 5:49-81

Harper D (1996) Wing and Leg problems (Pigeons). In: Beynon H, Forbes A, Harcourt-Brown H (eds) BSAVA Manual of Raptors, Pigeons and Waterfowl. Brittish Small Animal Veterinary Association Limited, Cheltenham, Gloucestershire, UK, pp 254-257

Harris M, Diaz-Figueroa O, Lauer S, Burkert B, Tully T (2007) Complications associated with conjoined intreamedullary pin placement for a femorotibial joint luxation in a Solomon Island Eclectus Parrot (*Eclectus roratus solomonensis*). J Avian Med Surg 21:299-306

Hatt J-M (1999) Non-infectious diseases of the skeletal system in pet birds. In: Kaleta FE, Krautwald-Junghanns Maria -Elisabeth (ed) Kompendium der Ziervgelkrankheiten, 3rd edn. Schlütersche Verlagsgesellschaft mbH & Co.KG, Hannover, pp 139-159

Hatt J-M, Christen C (2004) Practical considerations for the use of the tubular external fixator (F.E.S.S.A.) in the treatement of fractures in birds of prey. In: Joint BVZS, WAWV, ZSL and RVC Conference, 12-14 November 2004, London, Great Britain pp 118-120

Hatt J-M, Christen C, Sandmeier P (2007) Clinical application of an external fixator in the repair of bone fractures in 28 birds. Vet Rec 160:188-194

Hatt J-M, Sandmeier P (2003) Clinical application of the FESSA tubular external skeletal fixator in fracture repair of birds. In: Proc 7th Eur Assoc Avian Vet Conf, 22-26 April 2003. Teneriffa, Spain, pp 4-5

Hayes G, Alexander RM (1983) The hopping gait of crows (*Corvidae*) and other bipeds. J Zool Soc Lond 200:205-213

Helmer P (2006) Surgical resolution of orthopedic disorders. In: Harrison J, Lightfoot L (eds) Clinical Avian Medicine, vol II. Spix Publishing Inc, Palm Beach, Florida, US, pp 760-773

Henderson B, Pettipher E (1985) The synovial lining cell: Biology and pathobiology. Semin Arthritis Rheum 15:1-32

Henderson R, Olsen D, Yngve D (2002) Corrective osteotomy of the avian tibiotarsus. Exotic DVM 4.4:29-31

Hepburn D (1889) The development of diarthrodial joints in bird and mammals. J Anat Physiol 23:507-522

Hernadez-Divers SJ, Gladden J, Christian M, Hatt J-M (2007) Application of F.E.S.S.A. external fixation for long bone fractures in birds. In: Proc Veterinarian 28th Annu Conf Assoc Avian Vet/ Assoc Exot Mam Vet, Providence, Rhode-Island, USA

Hess E (1994) Management of orthopedic problems of the avian pelvic limb. Semin Avian Exot Pet Med 3:63-72

Holz P (1992) Luxation of the stifle joint in a Major Mitchell cockatoo. Vet Rec 130:34

Holz P (2003) Coracoid fractures in wild birds: repair and outcomes. Aust Vet J 81:469-471

Huff G, Huff W, Rath N, Balog J (2000) Turkey osteomyelitis complex. Poult Sci 79:1050-1056

Hulse DA, Shires P (1986) Multiple ligament injury of the stifle joint in the dog. J Am Anim Hosp Assoc 22:105-110

Hummel G (2000) Anatomie und Physiologie der Vögel. Eugen Ulmer GmbH Verlag, Giessen

Ireland P, Rogers J, Myers K (1986) Location of the instanteous center of joint rotation in the normal canine stifle. Am J Vet Res 47:837-840

Jaegger G, Marcellin-Little J, Levine D (2002a) Reliability of goniometry in Labrador Retrievers. Am J Vet Res 63:979-986

Jaegger G, Marcellin-Little JD, Levine D (2002b) Reliability of goniometry in Labrador Retrievers. Am J Vet Res 63:979-986

Jaffe M, Fitch R, Rich G, Tully T (2000) Medial release and extracapsular stabilization in a 7-month old blue and gold macaw (*Ara ararauna*) with a grade IV medial patella luxation. In: Proc Conf Association of Avian Veterinarians, pp 101-104

Jenkins R (1993) Postoperative care of the avian patient. Semin Avian Exot Pet Med 2:97-102

Jortikka M et al. (1997) Immobilisation causes longlasting matrix changes both in the immobilised and contralateral joint cartilage. Anna Rheum Dis 56:255-261

Jurvelin J, Kiviranta I, Saamanen A, et al (1989) Partial restoration of immobilization-induced softening of canine articular cartilage after remobilization of the knee (stifle) joint. J Orthop Res 7:352-358

Jurvelin J, Kiviranta I, Tammi M, et al (1986) Softening of canine articular after immobilization of the knee joint. Clin Orthop 207:246-252

Keller W, Aron D, Rowland N, Odend'hal S, Brown C (1994) The effect of trans-stifle external skeletal fixation and hyaluronic acid therapy on articular cartilage in the dog. Vet Surg 23:119-128

Kestin S, Knowles T, Tinch A, Gregory N (1992) Prevalence of leg weakness in broiler chickens and its relationship with genotype. Vet Rec 131:190-194

King A, McLelland J (1984) Skeletomuscular System. In: King A, McLelland J (eds) Birds: Their Structure and Function, 2nd edn. Baillllere Tindall, Eastbourne, Essex, UK, pp 43-79

Kirkwood J (2000) Twisting and bending deformities of the long bones in growing birds. In: Samour H (ed) Avian Medicine. Harcourt Publishers Limited, London, England, pp 173-177

Knap K, Johnson L, Schulz K (2007) Fundamentals of physical rehabilitation. In: Fossum TW (ed) Small Animal Surgery, 3rd edn. Mosby Elsevier, St. Louis, Missuri, USA, p 111

Knox P, Levick J, McDonald J (1988) Synovial fluid-its mass, macromolecular content, and pressure in major limb joints of the rabbit. Q J Exp Physiol 73:33-46

König E, Misek I, Liebich G-H (2001) Nervensystem. In: König E, Liebich G-H (eds) Anatomie und Propädeutik des Geflügels. F.K. Schattauer Verlagsgesellschaft mbH, Stuttgart, pp 169-188

Krafczyk S (2001) Topographische Anatomie der Hintergliedmasse von Psittaziden. In: Institut für Veterinär-Anatomie,-Histologie und-Embryologie, vol. Doctoral. Justus-Liebig-Universität Giessen, Giessen, p 83

Kraus H, Toombs P, Ness GM (2003) External fixation in small animal practice. Blackwell Science Ltd, Oxford

Kreeger T, Walser M (1984) Carpometacarpal deformity in a Giant Canada Goose (*Branta canadensis maxima Delacour*). J Wild Dis 20:245-248

Labeeu F, Pasuch M, Toussaint P, van Erps S (1996) External fixation in war traumatology: report from the Rwandese war (October 1,1990 to August 1,1993). J Trauma 40:S223-S227

Levick J (1984) Blood flow and mass transport in synovial joints. In: Renkin E, Michel C (eds) Handbook of physiology, the Cardiovascular System, vol 4 the Microcirculation. American Physiology Society, Baltimore, pp 917-947

Levine D, Millis L, Marcellin-Little J (2005) Introduction to veterinary physical therapy. Vet Clin North Am Small Anim Pract 35:6

Linn A, Templer S, Paul-Murphy J, O'Brien T, Hartup K, Langenberg J (2003) Ultrasonographic imaging of the sandhill crane (*Grus canadensis*) intertarsal joint. J Zoo Wild Med 34:144-152

Livingston A (1994) Physiological basis for pain perception in animals. J Vet Anesth 21:73-77

Lubosch W (1910) Bau und Entstehung der Wirbeltiergelenke. G.Fisher, Jena

MacCoy D (1986) Techniques of fracture treatment in birds and their indications: External and Internal Fixation. In: Proc Annu Meet Assoc Avian Vet, pp 367-376

MacCoy D (1989) Excision arthroplasty for management of coxofemoral luxation in pet birds. J Am Vet Med Assoc 194:95-97

Machin L (2005) Avian Pain: Psysiology and evaluation. Compend Cont Educ Pract Vet Feb 2005:98-109

Maierl J, Liebich G-H, König E (2001) Beckenglidmassen (Membra pelvica). In: König E, Liebich G-H (eds) Anatomie und Propädeutik des Geflügels. Schattauer Verlagsgesellschaft mbH, Stuttgart, pp 55-73

Malinovsky L, Zemanek R (1970) Sensory nerve endings in the joint capsules of the large limb joints in the domestic hen (*Gallus domesticus*) and the Rook (*Corvus frugilegus*) Folia Morphol XVIII: 206-212

Mankin J, Dorfman H, Lippiello L, Zarins A (1971) Biochemical and metabolic abnormalities in articular cartilage from osteo-arthritic human hips: II. Correlation of morphology with biochemical and metabolic data. J Bone Joint Surg 53:523-537

Mann F, Wagner-Mann C, Tangner C (1988a) Manual goniometric measurement of the canine pelvic limb. J Am Anim Hosp Assoc 24:189-194

Mann FA, Wagner-Mann C, Tangner CH (1988b) Manual goniometric measurement of the canine pelvic limb. J Am Anim Hosp Assoc 24:189-194

Manning M, Rush J, Ellis D (1997) Physical therapy for the critically ill veterinary patients. The muscoloskeletal system. Compend Cont Educ Pract Vet 19:803-806

Marcellin-Little J (2004a) Management of traumatic stifle luxation in cats. In: Traumatology ESVOT (ed) 12th European Society of Veterinary Orthopedics and Traumatology Congress. European Society of Veterinary Orthopedics and Traumatology, Munich, pp 94-96

Marcellin-Little J (2004b) Update on hinged and circular external fixation. In: Traumatology ESVOT (ed) 12th European Society of Veterinary Orthopedics and Traumatology Congress. European Society of Veterinary Orthopedics and Traumatology, Munich, pp 86-88

Marinou K (2006) The contribution of ultrasonography to the diagnostic imaging of the canine stifle joint. In: Traumatology HSVOT (ed) Second Meeting of the Hellenic Veterinary Society for Orthopedics and Traumatology: Surgical knee joints diseases in small mammals. Hellenic Society of Veterinary Orthopedics and Traumatology, Athens, Greece, p 76

Martell M, Redig P (1985) Quantative evaluation of the physical condition of the raptor patient prior to release. Wild Rehabil 4:131-134

Martin A (1954) An electron microscope study of the cartilaginous matrix in the developing tibia of the fowl. J Embryol Exp Morphol 2:38-48

Martin D, Ringdahl C, Scherpelz J (1993a) Physical therapy for specific injuries in raptors. In: Redig P, Cooper J, Remple J, Hunter D (eds) Raptor Biomedicine. University of Minnesota Press Mineapolis

Martin H, Bruecker K, Herrick D, Scherpelz ea (1993b) Elbow luxation in raptors: a review of eight cases. In: Redig P, Cooper J, Remple J, Hunter D (eds) Raptor Biomedicine. University of Minessota Press, Minneapolis, pp 199-206

Martin H, Kabler R, Sealing L (1994) The avian coxofemoral joint: a review of regional anatomy and report of an open-reduction technique for repair of a coxofemoral luxation. J Assoc Avian Vet 8:164-172

Martin H, Ritchie W (1994) Orthopedic surgical techniques. In: Ritchie W, Harrison J, RL H (eds) Avian Medicine: Principles and Application, 1st edn. Wingers Publishing INC, Lake Worth, Florida, USA, pp 1139-1169

Matsas A, Taylor N, McBurney H (2000) Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. Gait Posture 11:46-53

McMillan M (1994) Imaging techniques. In: Ritchie W, Harrison J, Harrison L (eds) Avian Medicine: Principles and Application. Wingers Publishing Inc, Lake Worth, FL, pp 246-32

McNamee P, McCullagh J, Thorp B (1998) Study of leg weakness in two commercial broiler flocks. Vet Rec 143:131-135
Meij P, Hazewinkel A, Westerhof I (1996) Treatment of fracture and angular limb deformities of the tibiotarsus in birds by Type II external skeletal fixation. J Avian Med Surg 10:153-162
Menigaux C, Adam F, Guignard B, Sessler D, Chauvin M (2005) Preoperative Gabapentin decreases anxiety and improves early functional recovery from knee sugery. Anesth Analg 100:1394-1399
Meyrueis J, Masselot A, Meyrueis J (1993) Etude mécanique comparitive tridimensionnelle de fixateurs externes Déductions cliniques. Rev Chir Orthop 79:402-406
Meyrueis J, Mine J, Rochat G, Mayaudon J, Tripon P (1980) Etude mécanique comparative des fixateurs externes: le modèle du Service de Santé des Armées. Rev Chir Orthop 66:317-321
Milgram J, Slonim E, Kass PH, Shahar R (2004) A radiographic study of joint angles in standing dogs. Vet Compend Orthop Traumatol 17:82-90
Monk L, Preston A, McGowan L (2006) Effects of early intensive postoperative physiotherapy on limb function after tibial plateau leveling osteotomy in dog with deficiency of the cranial cruciate ligament. Am J Vet Res 67:529-536
Muir G, Gosline J, Steeves J (1996) Ontogeny of bipedal locomotion: walking and running in the chick. J Physiol 493:589-601
Muller M, Nafeez J (2007) Use of the FixEx tubulaire type F.E.S.S.A System for tibiotarsal fractures in falcons. Falco 29:25-28
Muratori G, Franceschini M (1945) Osservazioni sperimentali sullo svillupo delle articollazioni degli arti nell' embrione di pollo. Anna Univ Ferrara in Anat Umana, INS:43-60
Murphy J (2006) Pain management. In: Harison J, Lightfoot L (eds) Clinical Avian Medicine vol I. Spix Publishing Inc, Palm Beach, FL, USA
Mutalib A, Holland M, Barnes H, Boyle C (1996) Ultrasound for detecting osteomyelitis in turkeys. Avian Dis 40:321-325
Naldo L, Samour H (2002) Selected orthopedic cases in falcons in Saudi Arabia. Exotic DVM 4.4:11-13
Naldo L, Samour H (2004) Radiographic findings in captive falcons in Saudi Arabia. J Avian Med Surg 18:242-256
Nardin J (1991) Utilisation du fixateur externe du Service de Santé des Armées en chirurgie orthopédique vétéerinaire. In: Faculté de Médecine de Nantes. Universite de Nante, Nantes, p 100
Nickel R, Schummer A, Seiferle E (1998) Anatomy of the Domestc Birds. Verlag Paul-Parey Munich
Nicks K, Beneke M, Key M, Timson F (1989) Muscle fibre size and number following immobilisation atrophy. J Anat 163:1-5
Niven J (1933) The development in vivo and in vitro of the avian patella. Roux' Arch. Entw. mech. Org 128:480-501
O 'Rahilly R, Gardner E (1956) The development of the knee joint of the chick and its correlation with embryonic staging. J Morphol 98:49-87
O'Meara P (1993) Rehabilitation following reconstruction of the anterior cruciate ligament. Orthop 16:301-306
Olsen G, Redig P, Orosz S (2000) Limb dysfunction. In: Olsen G, Orosz S (eds) Manual of Avian Medicine, 1 edn. Mosby, MO, St. Louis, p 524.
Olsen J (1994) Anseriformes. In: Ritchie W, Harrison J, Harrison R (eds) Avian Medicine: Principles and Application. Wingers Publishers Inc, Lake Worth, FL, p 1380
Palmer A, Hulse D, Pollo F, Hyman W, Palmer D et al. (1991) Pin loosening in external skeletal fixation: The effects of pin design and implantation site. Vet Surg 20:343
Palmieri G, Minelli L, Botti M, Gazza F et al. (2005) Autonomic and sensitive somatic innervation of the ostrich elbow and knee joints articular capsule. Ital J Anat Embryol 110:111-123
Piermattei L, Flo L, De Camp E (2006) Handbook of Small Animal Orthopedics and Fracture repair, Fourth edn. Saunders Elsevier Inc, St. Louis, Missouri

Platt D (1996) Articular cartilage homeostasis and the role of growth factors and cytokines in regulating matrix composition. In: McIlwraith C, Trotter W (eds) Joint disease in the horse. W.B. saunders Company, Philadelphia, PE, USA, pp 29-70
Polacek P (1966) Receptors of the joints. Their structure variability and classification. Acta Facult. Med. Univ. Brunensis 23:1-107
Polacek P, Sklenska A, Malinovsky L (1966) Contribution to the problem of joint receptors in birds. Folia Morphol (Prague) 14:33-42
Pollock C (2002) Postoperative management of the exotic animal patient. Vet Clin North Am Exot Anim Pract 5:183-212
Pollock C, Carpenter JW, Antinoff N (2005) Birds. In: Carpenter J (ed) Exotic Animal Formulary, 3rd edn. Elsevier Saunders Inc, St Loius, MI, USA, p 564
Pontzer H et al. (2006) Trabecular bone in the bird knee responds with high sensitivity to changes in load orientation. J Exp Biol 209:57-65
Radin E, Rose R (1986) Role of subchondral bone in the initiation and progression of cartilage damage. Clin Orthop 213:34-40
Rajchard J, Rachac V (2003) Defective wing delevopment in black-headed gull (*Larus ridibundus*) - case report. Vet Med 48:373-374
Rauber A (1867) Untersuchungen über das Vorkommen und die Bedeutung der Vater'schen Körper. C. Fritsch, München
Redig P (1986) A clinical review of the orthopedic techniques used in the rehabilitation of raptors. In: Fowler M (ed) Zoo and Wild Animal Medicine, 2nd edn. W.B. Saunders, Philadelphia, Pennsylvania, pp 388-401
Redig P (2000) The use of an external fixator-intramedullary pin tie-in (ESF-IM fixator) for treatment of longbone fractures in raptors. In: Lumeij J, JD R, Redig P, Lierz M, Cooper J (eds) Raptor Biomedicine III, 1st edn. Zoological Education Network, Lake Worth, pp 239-253
Redig P (2001) Effective methods for management of avian fractures and other orthopaedic problems. In: Korbel T (ed) 6th European AAV-DVG Conference/ 4th ECAMS Meeting. German Veterinary Medical Society, Munich, Germany
Reich T, Gefen A (2006) Effect of trabecular bone loss on cortical strain rate during impact in an in vitro model of avian femur. Biomed Eng Online 5:10
Reichler I, von Werthern C, Montavon P (1997) Der tubuläre fixateur externe (FESSA): klinische Anwendungen zur Frakturversorgung bei 6 Zwerghunden und 20 Katzen. Kleintierpraxis 42:407-419
Reilly S (2000) Locomotion in the Quail (*Coturnix japonica*): the kinematics of walking and increasing speed. J Morphol 243:173-185
Reiter K, Bessei W (1997) Gait analysis in laying hens and broilers with and without leg disorders. Equine Vet J Suppl 23:110-112
Remple J, Al-Ashbal A (1993) Raptor bumblefoot: another look at histopathology and pathogenesis. In: Redig P, Cooper J, Remple J, Hunter D (eds) Raptor Biomedicine. University of Minnesota Press, Minneapolis, UK
Reuleaux F (1876) The kinematics of machinery: outlines of a Theory of Machines. MacMillan, London
Risi E, Ordonneau D, Gauthier O (2005) Two cases of femoral head luxations in cormorants (*Phalacrocorax carbo*) treated with a modified Meij-Hazenwinkel-Nap technique. In: Proc 8th Eur Assoc Avian Vet / 6th Scientific ECAMS meeting Arles, France, pp 190-195
Roberts J, Scales A (2004) Adjusting muscle function to demand: joint work during acceleration in wild turkeys. J Exp Biol 207:4165-4174
Robins M (1990) The canine stifle. In: Whittick G (ed) Canine Orthopedics, 2nd edn. Lea & Febiger, London, pp 693-760
Rochat C, Hoover P, Di Gesualdo L (2005) Repair of a tibiotarsal varus malunion in a bald eagle (*Haliaeetus leucocephalus*) with a Type IA hybrid external skeletal fixator. J Avian Med Surg 19:121-129
Rosenthal K (2002) Avian radiography: how to interpret what you are seeing. In: Proc Conf Avian Vet, pp 297-300

Rosenthal K, Hillyer E, Mathiessen D (1994) Stifle luxation repair in a moluccan cockatoo and a barn owl. J Assoc Avian Vet 8:173-178

Rothschild M, Panza R (2006) Osteoarthritis is for the birds. Clin Rheum 25:645-647

Roush J (1980) Avian orthopedics. In: Kirk R (ed) Current Veterinary Therapy VII edn. SAUNDERS WB, Philadelphia, USA, pp 662-673

Roy S (1970) Ultrastructure of articular cartilage in experimental immobilization Anna Rheum Dis 24:634-642

Rubel G, Isenbugel E, Wolvekamp P (1991) Atlas of diagnostic radiology of exotic pets: small mammals, birds, reptiles and amphibians. Saunders WB, Philadelphia, PA

Rubenson J, Lloyd D, Besier T, Heliams D, Fournier A (2007) Running in ostriches (*Struthio camelus*): three-dimensional joint axes alignment and joint kinematics. J Exp Biol 210:2548-2562

Ruberte J, König EH, Liebich G-H (2001) Organe des Herz-Kreislauf-Systems. In: König E, Liebich G-H (eds) Anatomie und Propädeutik des Geflügels. Schattauer Verlagsgesselschaft mbH, Stuttgart, Deutschland, pp 143-160

Rupley E (1997) Muscoskeletal signs. In: Rupley E (ed) Manual of Avian Practice. Saunders W.B. Company, pp 198-217

Salomon F (1993) Lehrbuch der Geflügelanatomie. Gustav Fischer Verlag, Jena, Deutschland

Salomon F, Geyer H, Gille U (2005) Anatomie für die Tiermedizin. Enke Verlag in MVS, Stuttgart

Samour H, Naldo L (2007) Anatomical and clinical radiology of birds of prey. Saunders Elsevier

Samson J (1997) Prevalent diseases of ostrich chicks farmed in Canada. Can Vet J 38:425-428

Satterfield C, O'Rourke I (1981) External skeletal fixation in avian orthopedics, using a modified through-and-through Kirschner-Ehmer splint technique (the Boston technique). J Am Anim Hosp Assoc 17:635-637

Saunders Gross D, Walker J, Levine D (2005) Joint mobilization. In: Levine D, Millis L, Marcellin-Little J, Taylor A (eds) Vet Clin North Am Small Anim Pract. Elsevier pp 1287-1315

Schuster S (1996) Untersuchungen zu Häufigkeit, Lokalisation und Art von Frakturen beim Vogel. In: Institut für Geflügelkrankheiten. Justus-Liebig Universität, Giessen, p 150

Selmi L, Lins T, Barbudo-Selmi R, Mendes M (2003) Instantaneous center of motion following ex-vivo extra articular stabilization for the cranial cruciate ligament-deficient stifle. Cienc Rural 33:875-880

Shelbourne K, Nitz P (1990) Accelerated rehabilitation after anterior cruciate ligament reconstruction. Am J Sports Med 18:292-299

Sklenska A (1967) Joint receptors of the rabbit (*Oryctolagus cuniculus*). Doctoral thesis. University of Brno, Brno

Sklenska A (1969) Über Unterschiede in Häufigkeit, Verteilung und Struktur der Rezeptoren in einigen grossen Gelenken der Extremitäaten von Wirbeltieren. Z Mikroskop Anat Fors 80:249-259

Sklenska A (1971) Die sensible Innervation der Kapseln der grossen Extremitätengelenke bei der Hausente. Zool Listy

Sklenska A, Janska H (1972) Sensory Innervation of the large limb joints of the European Pochard (*Aythya ferina L.*). Folia Morphol 20:6-13

Smith B, Smith S (1992) Atlas of avian radiographic anatomy. Saunders WB, Philadelphia, PA

Smith B, Smith S (1997) Radiology. In: Altman B, Clubb L, Dorrestein M, Quesenberry K (eds) Avian Medicine and Surgery. Saunders WB, Philadelphia, PA, pp 170-199

Sonnenschein A (1951) Die Evolution des Kniegelenkes innerhalb der Wirbeltierreihe. Acta Anat 13:288-328

Sood S (1971) A study of the effects of experimental immobilization on rabbit articular cartilage. J Anat 108:497-507

Souza M, Fields L, Degernes A (2004) Thoracic and pelvic limb fracture and luxation management in raptors: A five-year retrospective study. J Wild Rehabil 27:5-13
Stone G, Walser M, Redig P, Rings B, Howard J (1999) Synovial chondromatosis in raptors. J Wild Dis 35:137-140
Suedmeyer K (1992) Post-anesthetic recovery of long-legged birds. J Assoc Avian Vet 6:92
Taylor A (1992) Postsurgical physical therapy: the missing link. Compend Cont Educ Pract Vet 14:1583-1593
Thompson R, Bassett C (1970) Histological observations on experimentally induced degeneration of articular cartilage. J Bone Joint Surg 52-A:435-443
Thorp B (1988a) Pattern of vascular canals in the bone extremities of the pelvic appendicular skeleton in broiler type fowl. Res Vet Sci 44:112-124
Thorp B (1988b) Vascular pattern of the developing knee joint in the domestic fowl. Res Vet Sci 44:89-99
Thorp B, Duff S (1988) Effect of unilateral weight-bearing on pelvic limb development in broiler fowls: vascular studies. Res Vet Sci 44:164-174
Todhunter J (1996) Section I: General Principles of Joint Pathobiology. Chapter 1: Anatomy and physiology of synovial joints. In: McIlwraith C, Trotter W (eds) Joint Disease in the Horse. W.B. Saunders Company, Philadelphia, pp 1-28
Toombs P (1992) Transarticular application of external skeletal fixation. Vet Clin North Am Small Anim Pract 22:181-194
Troyer H (1975) The effect of short-term immobilization on the rabbit knee joint cartilage: A histolochemical study. Clin Orthop 107:249-257
Turner S, Powell E, NG SS (1989) The effect of ultrasound on the healing of repaired cockerel tendon: is collagen cross-linkage a factor? J Hand Surg 14B: 428-433
van Bree H (2006) Diagnostic imaging of the canine stifle. In: Traumatology HSVOT (ed) Second meeting of the Hellenic Veterinary Society for Orthopedics and Traumatology: Surgical knee joint diseases in small mammals. Athens, Greece, pp 9-12
van Wettere A, Redig P (2004) Arthrodesis as a treatment for metacarpophalangeal joint luxation in 2 raptors. J Avian Med Surg 18:23-29
Vasseur B (2003) Stifle joint. In: Slatter D (ed) Textbook of Small Animal Surgery, 3rd edn. Saunders, pp 2090-2133
Venkatesan N, Thorp B, Hulmes D (1999) Articular cartilage proteoglycan metabolism in avian degenerative joint disease: Effects of strain selection and body weight. Connect Tissue Res 40:199-208
Verstappen M, Aerts P, van Damme R (2000) Terrestrial locomotion in the Black-billed magpie. Kinematic analysis of walking, running and out of phase hopping. J Exp Biol 203:2159-2170
Villaverde S, de la Vibora B, Gonzalez R, Freire M, Penà Lopez M et al. (2005) Management of the femorotibial luxation by coaptation splinting, intramedullary pins, external skeletal fixtor and tension bands: a pilot study in domestic pigeons (*Columba livia domestica*). In: Proc 8th Eur Assoc Avian Vet / 6th Scientific ECAMS meeting Arles, France, pp 196-202
Voss K, Lieskovsky J (2007) Trauma-induced growth abnormalities of the distal radius in three cats. J Feline Med Surg 9:117-123
Wagner M (2004) Die Osteologie der Hinterextremität und des Beckengürtels beim Afrikanischen Strauß (*Struthio camelus Linne* 1758). In: Department für Pathobiologie, vol. Doktorarbeit. Veterinärmedizinische Universität Wien, Wien
Watkins A, Riddle L, Lamb L, Personius J (1991) Reliability of goniometric measurements and visual estimates of knee range of motion obtained in a clinical setting. Phys Ther 71:90-97
Weeks C, Danbury T, Davies H, Hunt P, Kestin S (2000) The behaviour of broiler chickens and its modification by lameness. Appl Anim Behav Sci 67:111-125
Weeks C, Knowles T, Gordon R, Kerr A et al (2002) New method for objectively assessing lameness in broiler chickens. Vet Rec 151:762-764

Wendt K (2000) Topographische Anatomie der Hintergliedmaße beim Habicht (*Accipiter gentilis Linne*,1758). In: Institut für Veterinär-Anatomie-Histologie und -Embryologie vol. Dr.Med.Vet. Justus-Liebig-Universität Giessen, Giessen, p 60

Wimsatt J, Dressen P, Dennison C, Tumer A (2000) Ultrasound therapy for the prevention and correction of contractures and bone mineral loss associated with wing bandaging in the domestic pigeon (*Columba livia*). J Zoo Wild Med 31:190-195

Wink C, Elsey R, Onge MS, Zimmy M (1989) Neural elements in the cruciate ligaments and menisci of the knee joint of the American alligator (*Alligator mississippiensis*). J Morphol 202:165-172

Wobeser G, Leighton F, Chalmers A, Pharr J (1981) Shoulder luxation in Snow and Ross' Geese. J Wildl Manage 45:1030-1031

Zantop W (2000) Correcting selected orthopedic disorders in neonatal psittacines. Exotic DVM 2.2:23-27

Zeffer L, Johansson L, Marmebro A (2003) Functional correlation between habitat use and leg morphology in birds (*Aves*). Biol J Linn Soc Lond 79:461-484

Zehnder A, Wyre N, Kottwitz J, Brown C (2007) Physical rehabilitation in avian species In: Proc Assoc Avian Vet, Rhode Island, USA, pp 73-79

Zollinger T, Backues K, Burgos-Rodriguez A (2005) Correction of angular limb deformity in two subspecies of flamingo (*Phoenicopterus ruber*) utilizing a transphyseal bridging technique. J Zoo Wild Med 36:689-697

Zonghuan W (1997) Diagnosis and therapy of a caput humeri luxation in an ostrich. Chin J Vet Sci Tech 27:36-37

Zsivanovits P, Monks D, Forbes A (2006) Bilateral valgus deformity of the distal wings (Angel Wing) in a Northern Goshawk (*Accipiter gentilis*). J Avian Med Surg 20:21-26

9 Annexes

ANNEX I: Photographic anatomy of pigeon femorotibial joint

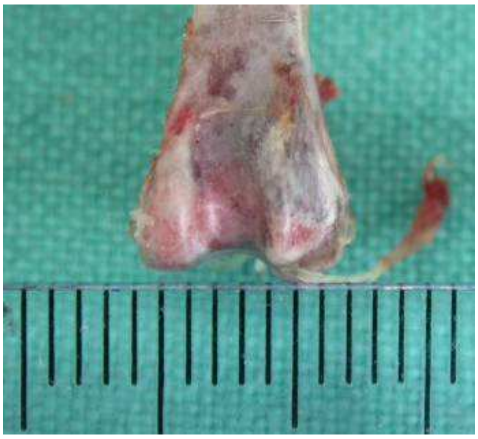


Figure A: Distal femur (scale in cm)

Figure B: Proximal tibiotarsus

Figure C: Lateral view of stifle with articular capsule, lateral collateral ligament and infrapatellar fat pad.

Figure D: Transverse ligament

Figure E: Cranial cruciate ligament route

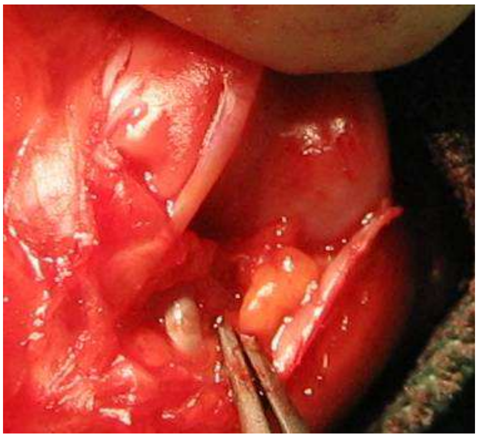


Figure F: Cranial cruciate ligament insertion (intra-operative)

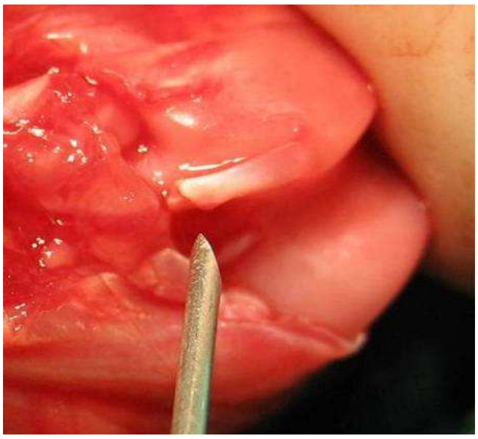


Figure G: Caudal cruciate insertion insertion

Figure H: Dorsal view of the menisci and fibular head

Figure I: Menisci and fibula

ANNEX II: Knee joint flexion-extension range in different gaits and species

Species	Knee joint angle (Flexion-Extension in degrees)			Source
	Walking (slow)	Running	Other	
Ratites				
Ostrich	85-130	70-118	10-15 (varus/valgus in run)	(Abourachid and Renous 2000; Rubenson et al. 2007)
Rhea	90-105			(Abourachid and Renous 2000)
Emus	75-90			(Abourachid and Renous 2000)
Kiwi	30-65			(Abourachid and Renous 2000)
Cassowary	75-115			(Abourachid and Renous 2000)
Game birds				
Guinea fowl	46,3 ±1,8-120			(Gatesy 1999b)
Wild turkey	63-145	105-120	82-132 (moderate acceleration)	(Roberts and Scales 2004)
Quail	53-114			(Reilly 2000)
Coraciformes				
Magpie	50±12-143±9	148±13	45±13-143±20 (Take off) 70±13-146±6 (Landing)	(Verstappen et al. 2000)
Pigeon	47-144	38-144	50-136 (moderate walking)	(Cracraft 1971)
Reptiles				
Lizard	60-90			(Reilly 2000)
Alligator	40-90			(Reilly 2000)
Mammals				
Dog	42-162 28-172 138±8		145 (Standing)	(Mann et al. 1988b; Carpenter and Cooper 2000a; Jaegger et al. 2002b; Milgram et al. 2004)
Human	64,7-66,9 (Flexion) 111-66 (PROM)		170 (mid-stance phase)	(Watkins et al. 1991; Matsas et al. 2000; Alexander 2004)

ANNEX III: Monitoring protocol

DATE					"Daily"	*CLINICAL*	*X-RAY 2*	*HISTO*	
BIRD					**ESF COMPLICATIONS**				
RING					PIN TRACT INFECTIONS				
"Daily"					Soft tissue sepsis				
GENERAL CONDITION					Focal osteomyelitis				
Weight					Ring sequestrum				
Food Intake					*FIXATOR PROBLEMS*				
Grit Intake					Premature pin loosening				
Faeces Production					Pin bending/fragment				
Faeces Appearance					Unstable configuration				
Haematology					Pressure necrosis of skin				
Mental Status					Tardy bone union				
Activity in aviary					Iatrogenic bone fracture				
					DJD signs				
"Daily"									
LAMENESS					**ROM (Flexion) in degrees**	Pre-OP	After 3 weeks	After 6 weeks	
Non lame	**0**				1st measurement				
Slight lame	**1**				2nd measurement				
Obvious lame but walking	**2**				3rd measurement				
Obvious lame but coaxed to move	**3**				***MEAN***				
Intermittent non-weight bearing (standing)	**4**				**ROM (Extension)**	Pre-OP	After 3 weeks	After 6 weeks	
Consistent non-weight bearing (recumbent)	**5**				1st measurement				
					2nd measurement				
"Daily"					3rd measurement				
					MEAN				
BUMBLEFOOT					**THIGH CIRCUMFERENCE (TC) in cm**	Pre-OP	After 3 weeks	After 6 weeks	**THIGH THICKNESS**
Grade I					1st measurement				
Grade II					2nd measurement				
Grade III					3rd measurement				
Grade IV					***MEAN***				
Grade V									

ANNEX IV
Post-mortem protocol

A)	GENERAL INFORMATION
Date	
Bird	
Ring	
Euthanasia Time	
Duration till death	
Drug Quantity (ml)	
Examiner	

B)	STIFLE JOINT POST-MORTEM EXAMINATION	
	Right Stifle	Left Stifle
Intracapsular Haematoma		
Articular Capsule condition		
Normal		
Thickened		
Ruptured		
Fibrotic		
Artificial LCL condition		
Suture rupture		
Suture in place		
Knots loosened		
Screw in place		
Screw loosened but still in place		
Screw out of capsule but stable		
Screw almost out of the bone		

C) Muscle Samples	Check
Right Femorotibialis & Gastrocnemius Muscles (Operated)	
Left Femorotibialis & Gastrocnemius Muscles (Healthy)	

D) Stifle Samples	Check
Right Stifle (Operated)	
Left Stifle (Healthy)	
Screw removal	
Motion after screw removal	
0= no axial or rotation motion	
1= slight	
2= major	

Notes

ANNEX IV (continued)
Protocol for the evaluation of the macroscopic characteristics of the synovial fluid in pigeons following experimental stifle surgery

Characteristics	Right Stifle Joint	Left Stifle Joint
Volume (total drop amount)		
Normal (2 “lentil” drops)		
Increased (more than 2 drops)		
Decreased (less than 2 drops)		
Viscosity test		
Normal (2 mm)		
Increased (> 2mm)		
Decreased (<2mm)		
Colour		
Pale-yellow		
Medium-yellow		
Clear		
Grey		
Bloody with clots		
Smear quality		

ANNEX V: Muscle histology evaluation index

General information	
Date	
Bird	
Ring	
Examiner	

Criteria

Lesion/ muscle	Actual No	**Centralisation of nuclei**		**Inflammation**		**Fibrosis**		**Fatty tissue**	
		0	≤ 5	0	no	0	No	0	normal
		1	5-10	1	acute	1	yes	1	extensive (more than 20 cells)
		2	11-20	2	subacute			2	extreme (more than 50 cells)
		3	≥20	3	chronic				

Abbreviations

GaLefLes	Gastrocnemius Left Lesions	**GaRigLes**	Gastrocnemius Right Lesions	**QuLefLes**	Quadriceps Left Lesions	**QuRigLes**	Quadriceps Right Lesions
GaLefCen	Gastrocnemius Left Centralization	**GaRigCen**	Gastrocnemius Right Centralization	**QuLefCen**	Quadriceps Left Centralization	**QuRigCen**	Quadriceps Right Centralization
GaLefInf	Gastrocnemius Left Inflammation	**GaRigInf**	Gastrocnemius Right Inflammation	**QuLefInf**	Quadriceps Left Inflammation	**QuRigInf**	Quadriceps Right Inflammation
GaLefFib	Gastrocnemius Left Fibrosis	**GaRigFib**	Gastrocnemius Right Fibrosis	**QuLefFib**	Quadriceps Left Fibrosis	**QuRigFib**	Quadriceps Right Fibrosis
GaLefFat	Gastrocnemius Left Fat Tissue	**GaRigFat**	Gastrocnemius Right Fat Tissue	**QuLefFat**	Quadriceps Left Fat Tissue	**QuRigFat**	Quadriceps Right Fat Tissue

ANNEX VI: Modified Mankin grading protocol for femorotibial cartilage evaluation of the present study

Date & Sample:

Tolouidine stain

Luxation	Amyloid deposits	Fibrosis		Grade
			Absence	0
			Possible	1
			Presence	2

Mankin Grading		
I	Structure	Grade
	a.Normal	0
	b.Surface with irregularities	1
	c. Pannus and surface irregularities	2
	d. Clefts to transitional zone	3
	e. Clefts to radial zone	4
	f. Clefts to calcified zone	5
	g. Complete disorganization	6
II	Cells	
	a. Normal	0
	b. Diffuse hypercellularity	1
	c. Clusters	2
	d. Hypocellularity	3
III	Tolouidine –O Staining	
	a. Normal	0
	b. Slight reduction	1
	c. Moderate reduction	2
	d. Severe reduction	3
	e. No dye noted	4
IV	Tidemark integrity	
	a. Intact	0
	b. Crossed by vessels	1

Van Kossa/Mc Neal stain

I	Osteoid locations	Grade
	0-5 locations	0
	5-10 locations	1
	>10 locations	2
II	Osteophytes	
	Absence	0
	Possible	1
	Presence	2

H & E stain

Inflammation		Grade
	Normal appearance	0
	Villous hyperplasia of synovial membrane	1
	Lymphocytes/Macrophages	2

ANNEX VII: Surgery and anesthesia time in the present study

Pigeon No	Ring Colour	Anaesthesia time	Surgery time
		minutes	minutes
1	Red	175	100
2	white	255	165
3	black	180	135
4	yellow	180	125
5	Grey	175	125
6	Lila	175	130
7	Blue	170	120
8	green	140	95
	Mean	181.25	124.37
	Standard deviation	32.48	21.61

ANNEX VIII: External skeletal fixation complication in the present study

Pigeon No	Ring Colour	Minor pin tract infection	Mild swelling	Inaccurate hinge position	ESF screw loosening	ESF pin loosening	Tibiotarsal haematoma	Intra articular haematoma
1	red	X	-		-	-	-	-
2	white	X	-		-	-	-	-
3	black	X	-	X	-	-	-	-
4	yellow	-	-		-	-	-	-
5	grey	X	X		X	X	X	
6	lila	X	-		-	-	-	X
7	blue	X	-		-	-	-	-
8	green	-	X		-	-	-	-

ANNEX IX: Individual mean weight in (grams) for the treatment period

Pigeon No	Treatment Group	Operation Day	First Week	Second Week	Third Week	Fourth Week	Fifth Week	Sixth Week	Euthanasia Day
1	A	350	328	334	348	290	336	346	336
2	B	308	304	306	328	300	312	324	298
3	A	330	326	340	342	328	336	334	328
4	B	315	312	310	310	292	318	304	294
5	A	302	296	288	304	282	290	306	300
6	B	376	380	384	380	368	364	368	362
7	A	300	298	300	278	276	304	296	288
8	B	340	328	342	322	318	324	328	312

INDEX
A: EPG (Early Physiotherapy Group)
B: LPG (Late Physiotherapy Group)

ANNEX X: Individual mean Range of Motion (ROM) in pigeons following experimental right stifle surgery in the third and sixth week

Pigeon No	**Treatment Group**	Flexion Pre-surgical Right	Flexion in 3rd week Right	Flexion in 6th week Right	Flexion in 6th week Left	Extension Pre-surgical Right	Extension in 3rd week Right	Extension in 6th week Right	Extension in 6th week Left
1	A	32.7	49.3	32.7	28.7	180.0	120.0	121.3	180.0
2	B	29.7	48.0	53.3	31.3	180.0	120.7	106.7	180.7
3	A	33.0	50.7	42.3	33.3	180.0	118.7	145.7	180.0
4	B	34.0	46.7	51.3	22.3	180.0	109.3	118.0	180.0
5	A	31.0	45.3	50.7	25.3	179.7	140.7	136.0	177.7
6	B	30.3	37.0	30.0	21.7	180.0	131.3	128.7	180.0
7	A	31.0	45.0	21.7	21.7	179.7	138.3	158.0	179.7
8	B	30.0	37.0	24.7	25.7	180.0	160.0	140.0	180.3

ANNEX XI: Individual mean thigh measurements in pigeons after right stifle surgery in third and sixth week

Pigeon No	**Treatment Group**	TC Pre-surgical	TC in 3rd week Right	TC in 6th week Right	TC in 6th week Left	TTh Pre-surgical	TTh in 3rd week Right	TTh in 6th week Right	TTh in 6th week Left
1	A	5.70	5.50	5.70	5.67	2.27	1.90	2.40	2.93
2	B	5.17	6.43	5.73	5.63	2.37	1.93	2.13	2.73
3	A	5.33	6.33	5.77	5.53	2.60	2.40	2.37	2.70
4	B	5.20	5.07	5.40	5.57	2.57	1.60	1.80	2.67
5	A	5.17	5.87	5.47	5.70	2.80	2.57	2.23	3.07
6	B	5.33	5.57	5.37	5.57	2.67	2.33	2.47	2.97
7	A	5.20	5.77	5.23	5.77	2.80	2.37	1.93	2.77
8	B	5.27	5.93	5.13	5.33	2.30	2.17	2.07	3.00

INDEX
TC: Thigh circumference (periphery)
TTH: Thigh thickness

ANNEX XII: Individual lameness score in pigeons after right stifle surgery for the 6th week period

Pigeon No	**Treatment Group**	Operation Day	First Week	Second Week	Third Week	Fourth Week	Fifth Week	Sixth Week	Euthanasia Day
1	A	5	4 to 3 (3.5)	3	3	3	3	2	2
2	B	4 held in ext	4	4 to 3 (3.5)	4 to 3 (3.5)	4 to 3 (3.5)	3	3 to 2 (2.5)	2
3	A	5	4	4	4	4	3	3 to 2 (2.5)	2
4	B	4	4	3	3	3	3	2	2
5	A	4	4	4	4	4	4 to 3 (3.5)	4 to 3 (3.5)	3 to 2 (2.5)
6	B	4	4	4 to 3 (3.5)	4 to 3 (3.5)	4 to 3 (3.5)	3	2	2
7	A	4	4	3	3	4 to 3 (3.5)	3 to 2 (2.5)	2	2
8	B	4	4 to 3 (3.5)	4 to 5 (4.5)	4	4	3 to 2 (2.5)	2	2

ANNEX XII: Pododermatitis score per individual pigeon following stifle surgery

Pigeon No	**Treatment Group**	Operation Day	First Week	Second Week	Third Week	Fourth Week	Fifth Week	Sixth Week	Euthanasia Day
1	A	0	0	0	0	0	0	I	I
2	B	0	0	0	0	0	I	I	I
3	A	0	0	I L	I L	I	I	I	I
4	B	0	0	I	I	I	I	I	I
5	A	0	I L	I R	I R	I	I	I	I
6	B	0	I L	0	0	0	0	I	I
7	A	0	0	0	0	0	0	I R	I
8	B	0	I L	I L	0	0	0	I	I

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0: absence
IR: Grade I right foot
IL: Grade I left foot
I: Grade I both feet

ANNEX XIV: Post mortem examination of the femorotibial joint in pigeons of this study

Pigeon No	**Treatment Group**	Intracapsular haematoma Right	Articular capsule condition Right	ALCL condition Right	Motion after screw removal Right	Intracapsular haematoma Left	Articular capsule condition Left
1	A	-	Normal Little fibrotic	In place	1	-	Normal
2	B	due to arthrocentesis	Thickened Fibrotic	Screw loosened, head out of the capsule and out of bone (?)	0	-	Normal
3	A	due to arthrocentesis	Normal and little fibrotic	with fibrotic material	0	due to arthrocentesis	Normal
4	B	-	Thickened Fibrotic	In place	0	-	Normal
5	A	-	Thickened Fibrotic	In place	0	-	Normal
6	B	-	Thickened Fibrotic	In place	0	-	Normal
7	A	due to arthrocentesis	Thickened Fbrotic	In place	0	-	Normal
8	B	-	Thickened Fibrotic	In place	0	-	Normal

ANNEX XV: Individual macroscopic synovial fluid evaluation in the day of euthanasia

Pigeon No	**Treatment Group**	Volume Right	Volume Left	Colour Right	Colour Left	Viscosity Right	Viscosity Left	Smear Right	Smear Left
		droplets	droplets						
1	A	1	2	Pale yellow	Pale yellow	-	2mm	Done	Done
2	B	0.5	1.5	Bloody with clots	Clear	-	-	Done	Done
3	A	0.5	1	Bloody with clots	Bloody with clots	-	-	Done	Done
4	B	1	0.5	Grey to bloody	Bloody with clots	-	-	Done	Done
5	A	1	2	Medium yellow with clots	Pale yellow	2mm	3mm	Done but not satisfactory	Done
6	B	1+	1.5+	Medium yellow with clots	Pale yellow	-	3mm	Done but not satisfactory	Done
7	A	1	1.5	Pale yellow with few clots	Pale yellow with few clots	3-4mm	2-3mm	Done	Done
8	B	0.3	1.5	Bloody with clots	Pale yellow with clots	-	-	Done but not satisfactory	Done

ANNEX XVI: Individual muscle histology (Part 1: Gastrocnemius)

Pigeon No	**Treatment Group**	GaLef Les	GaLefCen	GaLef Inf	GaLef Fib	GaLef Fat	GaRig Les	GaRig Cen	GaRig Inf	GaRig Fib	GaRig Fat
1	A	0	0	0	0	0	1	1	0	0	1
2	B	1	1	0	0	1	0	0	0	0	1
3	A	0	0	1	0	1	0	0	0	0	1
4	B	0	0	0	0	1	0	0	0	0	1
5	A	1	2	0	0	1	1	3	0	0	1
6	B	0	0	0	0	1	5	3	0	0	1
7	A	0	0	0	0	2	0	0	0	0	2
8	B	0	0	0	0	1	2	1	0	0	1
9	Control	0	0	0	0	1	0	0	0	0	0
10	Control	0	0	0	0	0	1	3	3	1	1

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See ANNEX V

ANNEX XVI: Individual muscle histology (Part 2: Quadriceps/Femorotibialis)

Pigeon No	**Treatment Group**	QuLef Les	QuLefC en	QuLef Inf	QuLef Fib	QuLef Fat	QuRig Les	QuRig Cen	QuRig Inf	QuRig Fib	QuRig Fat
1	A	1	0	0	0	1	4	3	0	1	1
2	B	0	0	0	0	1	0	0	0	0	0
3	A	0	0	0	0	2	3	3	0	1	1
4	B	0	0	0	0	2	1	0	0	0	2
5	A	2	3	2	1	2	3	3	0	0	2
6	B	0	0	0	0	1	2	1	0	0	1
7	A	0	0	0	0	1	3	3	0	1	2
8	B	0	0	0	0	1	3	3	0	1	2
9	Control	0	0	0	0	1	1	0	0	0	1
10	Control	0	0	0	0	1	0	0	0	0	0

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ANNEX XVII: Individual score of the femorotibial joint histology examined for bone position, amyloid concetrations, fibrosis, inflammation, remodelling and osteophytes

Pigeon No	**Treatment Group**	Luxation Right	Amyloid Right	Fibrosis Right	Osteoid Right	Osteophytes Right	Inflammation Right	Luxation Left	Amyloid Left	Fibrosis Left	Osteoid Left	Osteophytes Left	Inflammation Left
1	A	1	0	0	0	0	0	0	0	0	0	0	0
2	B	0	0	1	0	1	0	0	0	0	0	0	0
3	A	1	0	0	0	0	0	0	0	0	0	0	0
4	B	0	0	1	0	2	0	0	0	0	0	0	0
5	A	1	0	0	0	1	0	0	0	0	0	0	0
6	B	1	0	0	0	0	0	0	0	0	0	0	0
7	A	2	0	0	0	1	0	0	0	0	0	0	0
8	B	1	0	0	0	2	0	0	0	0	0	0	0
9	Control	0	0	0	1	0	0	0	0	0	2	0	1
10	Control	0	0	0	0	0	0	0	0	0	0	1	0

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ANNEX XVIII: (A) Joint histology Mankin score for the femoral central part of the cartilage

Pigeon No	Treatment Group	Femur Central Structure Right	Femur Central Cell Right	Femur Central Toluidine Right	Femur Central Tidemark Right	Femur Central Structure Left	Femur Central Cell Left	Femur Central Toluidine Left	Femur Central Tidemark Left
1	A	2	0	0	0	0	0	0	0
2	B	4	0	0	1	0	0	0	0
3	A	5	1	0	0	0	0	0	0
4	B	0	0	0	0	0	0	0	0
5	A	0	0	0	0	2	0	0	0
6	B	2	0	0	0	0	0	0	0
7	A	2	0	0	0	0	0	0	0
8	B	2	0	0	0	1	0	0	0
9	Control	4	1	1	0	4	3	3	1
10	Control	5	0	0	0	0	0	0	0

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See ANNEX VI

ANNEX XVIII: (B) Joint histology Mankin score for the femoral peripheral part of the cartilage

Pigeon No	Treatment Group	Femur Peripheral Structure Right	Femur Peripheral Cell Right	Femur Peripheral Toluidine Right	Femur Peripheral Tidemark Right	Femur Peripheral Structure Left	Femur Peripheral Cell Left	Femur Peripheral Toluidine Left	Femur Peripheral Tidemark Left
1	A	0	0	0	0	3	0	0	0
2	B	0	0	1	0	0	0	0	0
3	A	2	0	0	0	0	0	0	0
4	B	0	0	0	0	0	0	0	0
5	A	0	0	0	0	0	0	0	0
6	B	0	0	0	0	0	0	0	0
7	A	2	0	0	0	0	0	0	0
8	B	0	0	0	0	0	0	0	0
9	Control	0	0	0	0	0	0	1	0
10	Control	0	0	0	0	0	0	0	0

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See ANNEX VI

ANNEX XVIII: (C) Joint histology Mankin score for the tibiotarsal central part of the cartilage

Pigeon No	Treatment Group	Tibiotarsal Central Structure Right	Tibiotarsal Central Cell Right	Tibiotarsal Central Toluidine Right	Tibiotarsal Central Tidemark Right	Tibiotarsal Central Structure Left	Tibiotarsal Central Cell Left	Tibiotarsal Central Toluidine Left	Tibiotarsal Central Tidemark Left
1	A	0	0	0	1	0	0	0	0
2	B	2	3	1	0	0	0	0	0
3	A	4	3	3	1	0	0	0	0
4	B	6	0	0	0	2	0	0	0
5	A	0	0	0	0	4	0	0	0
6	B	0	0	0	0	0	0	0	0
7	A	0	0	0	0	0	0	0	0
8	B	1	3	2	0	4	0	0	0
9	Control	0	0	0	0	0	1	0	0
10	Control	5	0	0	0	0	0	0	0

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ANNEX XVIII: (D) Joint histology Mankin score for the tibiotarsal peripheral part of the cartilage

Pigeon No	Treatment Group	Tibiotarsal Peripheral Structure Right	Tibiotarsal Peripheral Cell Right	Tibiotarsal Peripheral Toluidine Right	Tibiotarsal Peripherall Tidemark Right	Tibiotarsal Peripheral Structure Left	Tibiotarsal Peripheral Cell Left	Tibiotarsal Peripheral Toluidine Left	Tibiotarsal Peripheral Tidemark Left
1	A	0	0	0	0	0	0	0	0
2	B	2	3	0	1	2	0	0	0
3	A	0	0	0	0	0	0	0	0
4	B	0	0	0	0	0	0	0	0
5	A	0	0	0	0	0	0	0	0
6	B	0	2	0	0	2	3	0	0
7	A	2	0	0	0	0	0	0	0
8	B	0	0	0	0	0	0	0	0
9	Control	0	0	0	0	0	0	0	0
10	Control	0	0	0	0	0	0	0	0

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ANNEX XIX: Pigeon joint histology I

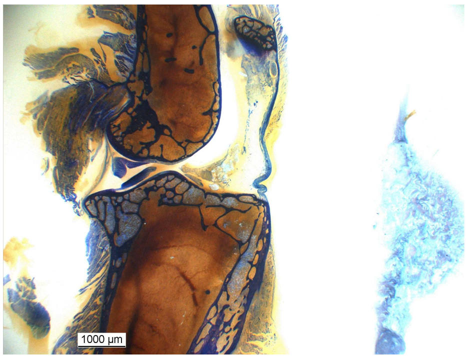

Figure 29: Normal bone position. The patella and patellar ligament can be seen (thick section, toluidine blue).

Figure 30: Normal position. Cranial cruciate visible (thick section, toluidine blue).

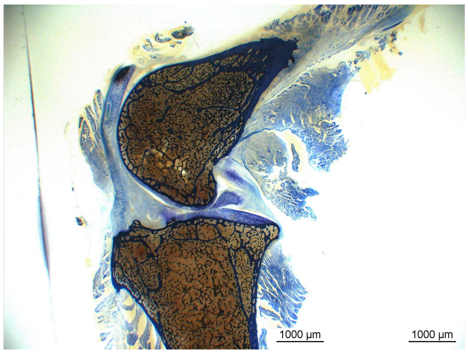

Figure 31: Possible luxation with excessive trabeculae (thick section, toluidine blue).

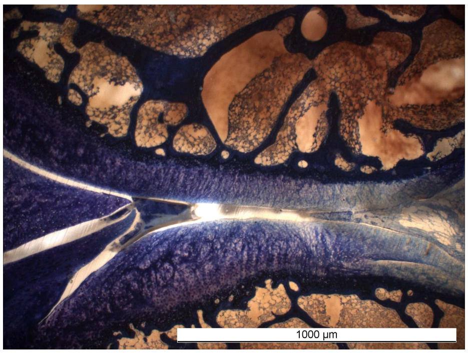

Figure 32: Normal cartilage central area (thick section, toluidine blue).

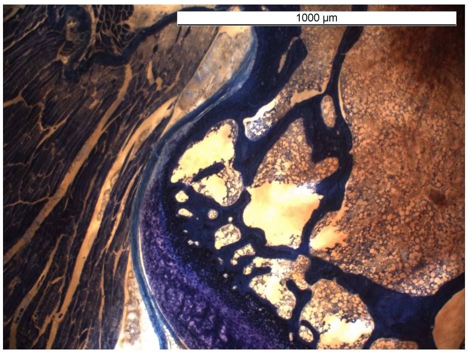

Figure 33: Normal caudal femur peripheral cartilage (thick section, toluidine blue)

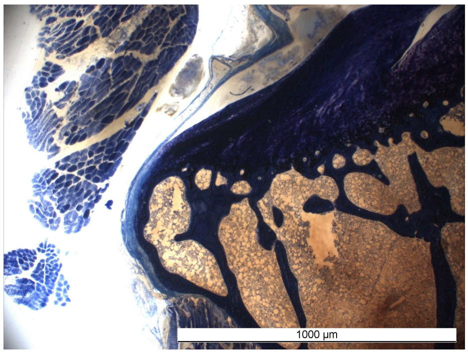

Figure 34: Normal caudal tibiotarsal peripheral cartilage (thick section, toluidine blue)

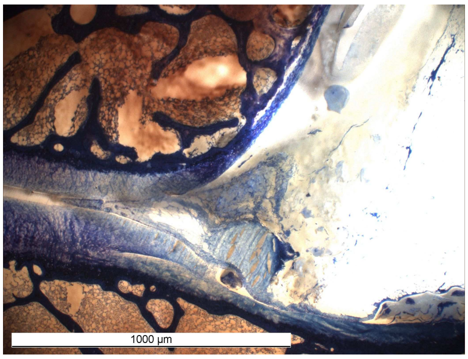

Figure 35: Normal cranial femur-tibiotarsal cartilage (thick section, toluidine blue)

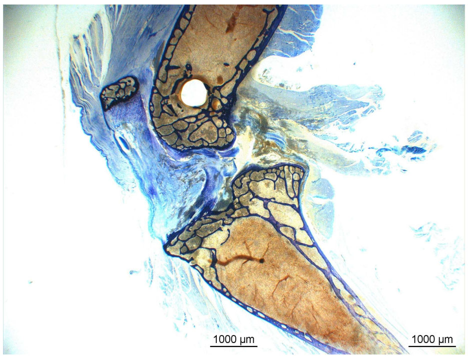

Figure 36: Total disorganization. Possible luxation. Bone screw hole visible (thick section, toluidine blue).

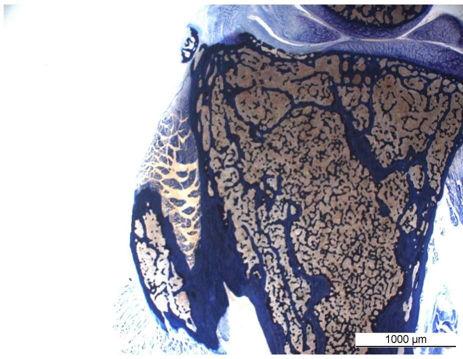

Figure 37: New bone formation in tibiotarsus (thick section, toluidine blue).

ANNEX XX: Pigeon joint histology II

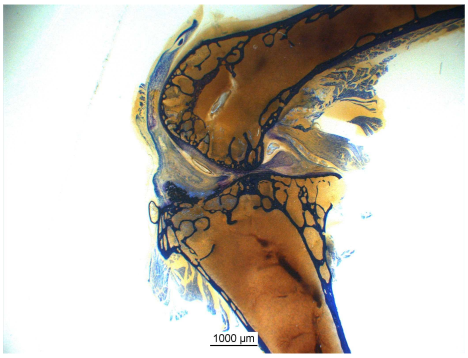

Figure 38: Osteophyte formation in cranial tibiotarsus. (thick section, toluidine blue)

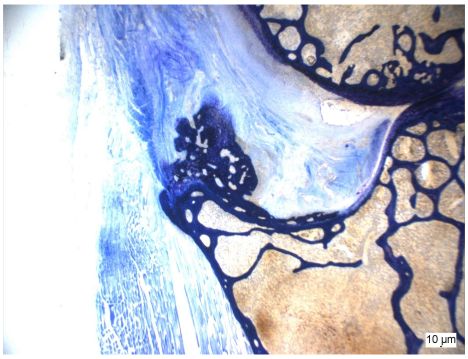

Figure 39: Osteophyte formation (closer view) (thick section, toluidine blue)

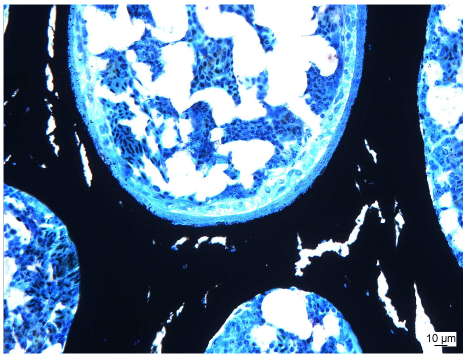

Figure 40: Osteoid area tibiotarsus (thin section, van Kossa/Mc Neal stain)

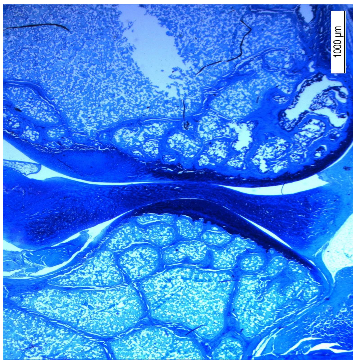

Figure 41: Normal menisci. (microscopic view) (thin section, toluidine blue).

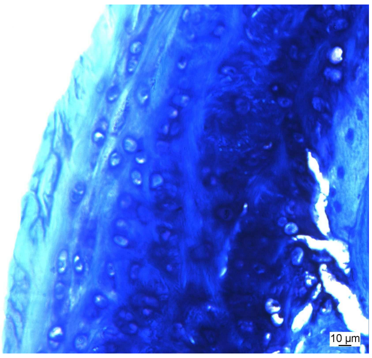

Figure 42: Normal cartilage central area (thin section, toluidine blue).

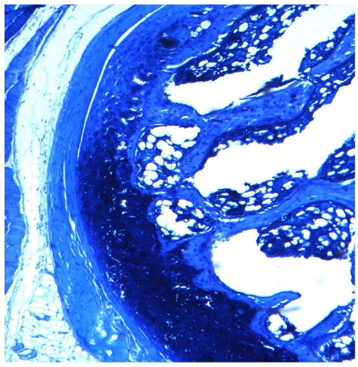

Figure 43: Normal cartilage peripheral area. Hypercellular area passed to normal hypocellular area (femoral condyle) (thin section, toluidine blue).

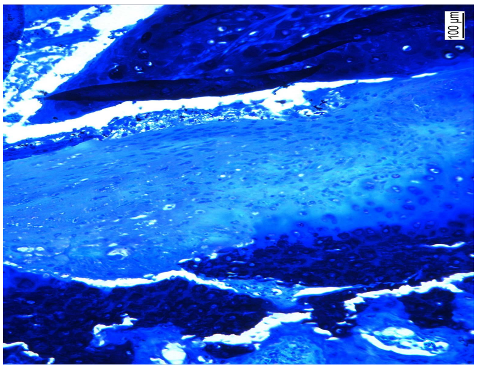

Figure 44: Irregular surface. Disrupted tidemark. Meniscus visible in the upper right corner (thin section, toluidine blue).

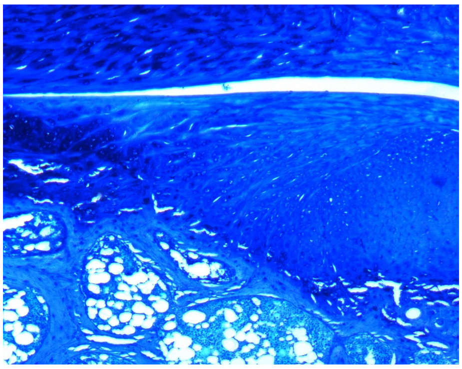

Figure 45: Pannus in compression central area of tibiotarsus (thin section, toluidine blue).

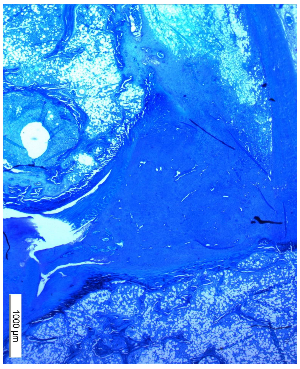

Figure 46: Fused fibrocartilage area in cranial femoral area. Hole of bone screw visible, containing fibrotic material (thin section, toluidine blue).

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